Towards a Framework for the Design and Development of a System for Practical Education in Electrical Engineering

by

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Declaration

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Dedication

For all those who can do, yet still choose to teach.
Thank You.

Abstract

How to educate undergraduate students in the practical aspects of engineering is a complex problem. To address it requires both a technical solution (referring to the equipment itself) as well as a study of education theory.

The ability to apply learned scientific knowledge in a practical way is a key tenet of engineering. Experiments are one of the principle ways whereby students learn to consolidate theory and practice. Practicals provide university students with experimenting opportunities which help to cement their theoretical knowledge as well as allowing them to gain experience working with real-world systems. However, if the equipment and systems in the laboratories are not well designed, or not designed for educational purposes, then the student becomes overwhelmed by it. In the end they learn how to use the experimental set-up itself, rather than what they are supposed to investigate with it.

When we developed new practical assignments for a final year module, we realised that the current equipment was indeed failing the students. To address this we first considered the use of commercially available solutions. But the equipment was not able to meet our requirements — mainly because the equipment was not designed for the education environment, had proprietary interfaces and was expensive. We then set about investigating the possibility of designing a new system for engineering practical education that could better address the requirements of the laboratory, as well as overcome the limitations of the commercial equipment.

We soon realised the complexity of such a proposal. Its successful execution would require a knowledge of engineering as well as of many other fields. Such a development would also require a detailed knowledge of the institution where the system is to be developed and used. But most significantly, the project is simply too complex for a single researcher or research group to complete alone; and nor should they. This system can have a very positive impact on both practical teaching as well as general research development, and it is only by sharing ownership that the project will progress beyond the most basic system.

To realise such a large shared project, and to make it sustainable, requires a detailed development framework — that would consolidate all the various requirements, provide a clear development road map and award researchers the freedom to innovate.

This exploratory study is aimed at the development of such a framework. We start by investigating current literature surrounding engineering education and laboratory systems development. We consider the current state of practical engineering at our university. (Our proposed method can also be used for other studies like this.) Furthermore, we advocate the continued development of engineering education research, presenting this study as a starting point to introduce the field to engineering researchers.

To develop requirements for the equipment itself, as well as to understand the limitations and challenges of its development, we designed three prototypes. We used solar photovoltaic practicals as an example case to limit the scope of the prototypes and help focus our endeavours.

Since this is an exploratory study there is a lot of potential for future research. However, we feel that development of the framework itself should take priority as it is the key towards opening development to the broader academic community.

Opsomming

Hoe om voorgraadse studente in die praktiese aspekte van ingenieurswese op te lei, bly 'n komplekse probleem. Om dit aan te spreek, vereis 'n tegniese oplossing (verwysende na die toerusting self) asook 'n studie van die onderrigsteorie.

Die vermoë om akademiese wetenskapskennis prakties toe te pas, is 'n kernbeginsel van ingenieurswese. Eksperimente tel onder die belangrikste maniere waardeur studente leer om teorie en praktyk bymekaar te bring. Praktiese klasse help universiteitstudente om te eksperimenteer, hul teoretiese kennis só te bevestig en ervaring van sisteme in die regte wêreld te kry. Word laboratoriumtoerusting en -sisteme egter swak ontwerp, of nie vir onderrigdoeleindes ontwerp nie, oorweldig dit die studente. Hulle leer uiteindelik hoe om 'n eksperimentele opstelling te gebruik eerder as om ervaring te verkry oor wát hulle met die opstelling moes ondersoek.

Met die opstel van nuwe praktiese opdragte vir 'n finalejaarmodule het ons besef die huidige toerusting laat studente inderdaad in die steek. Daarom het ons eers kommersieel beskikbare toerusting oorweeg, maar dit kon nie aan ons vereistes voldoen nie – hoofsaaklik omdat die toerusting nie vir die onderrigomgewing ontwerp was nie, eiendomsmatige koppelvlakke gehad het en te duur was. Ons het toe die moontlikheid van 'n nuut ontwerpte sisteem vir praktiese ingenieursonderrig ondersoek, wat beter sou voldoen aan die laboratoriumvereistes en die kommersieel beskikbare toerusting se beperkings kon oorkom.

Ons het egter gou besef hoe kompleks so 'n voorstel is. Om dit suksesvol uit te voer, is kennis van ingenieurswese, én vele ander velde, nodig asook 'n diepgaande kennis van die instelling waar die stelsel ontwikkel en gebruik word. Maar, die belangrikste, is dat so 'n projek bloot te kompleks is om deur een navorser of 'n navorsingspan alleen voltooi te word, en dít moet ook nie gebeur nie. Dié sisteem kan op praktiese onderrig asook navorsingsontwikkeling 'n sterk positiewe invloed hê, en slegs deur die projek se eienaarskap te deel, sal dit verder vorder as net die mees basiese stelsel.

Om so 'n omvattende, gedeelde projek te laat realiseer, en volhoubaar te maak, verg 'n gedetailleerde ontwikkelingsraamwerk – wat die verskeie vereistes sal konsolideer, sodoende duidelik rigting gee aan die ontwikkeling, en terselfdertyd vir navorsers die vryheid bied om te innoveer.

Hierdie verkennende studie is onderneem om so 'n raamwerk te ontwikkel. Ons begin met 'n ondersoek na die huidige literatuur oor ingenieursonderrig asook die ontwikkeling van sisteme vir laboratoriumgebruik. Die huidige stand van praktiese ingenieurswese by ons universiteit kom onder die soeklig. (Ons voorgestelde metode kan ook in soortgelyke studies gebruik word). Verder probeer bevorder ons hiermee volgehoue navorsingsontwikkeling oor ingenieursonderrig, as 'n beginpunt om hierdie navorsingsveld aan ingenieursnavorsers bekend te stel.

Om die toerusting se vereistes te ontwikkel, én die beperkings en uitdagings van sodanige ontwikkeling te verstaan, het ons drie prototipes ontwerp. Praktiese klasse oor fotovoltaïse sonkragstelsels is gebruik om die prototipes se omvang te beperk en ons pogings te fokus.

Omdat hierdie studie verkennend is, bevat dit baie moontlikhede vir toekomstige navorsingsaansluiting. Ons meen egter die raamwerk self se ontwikkeling moet voorrang geniet, want dit is die sleutel wat ontwikkeling onder die breër akademiese gemeenskap kan ontsluit.

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List of Abbreviations

ABET Accreditation Board for Engineering and Technology

ABS Acrylonitrile Butadiene Styrene

AC Alternating Current

ADC Analogue to Digital Converter

CES Committee of the Engineering Societies

CSI Computer Security Institute

CT Current Transformer

DAC Digital to Analogue Converter

DC Direct Current

DIS Data Interface Service

E&E Electrical and Electronic Engineering

EC 2000 Engineering Criteria 2000

ECPD Engineers' Council for Professional Development

ECSA Engineering Council of South Africa

ES414 Energy Systems 414

ESD Electrostatic Discharge

EU-OSHA European Agency for Safety and Health at Work

FBI Federal Bureau of Investigation

FIFO First-In-First-Out

GNU GNU's Not Unix!

GPL General Public License

HDMI High-Definition Multimedia Interface

HTTP Hypertext Transfer Protocol

HUD Heads-Up Display

HV-Lab High-Voltage Laboratory

I^{2}C Inter-Integrated Circuit

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

IP Internet Protocol

IP Intellectual Property

ISO International Organization for Standardization

JTAG Joint Test Action Group

LAN Local Area Network

LCD Liquid Crystal Display

LED Light Emitting Diode

Machine Lab Electrical Machines Laboratory

MCU Microcontroller

MODBUS Modicon Bus Standard

MOSFET Metal–Oxide–Semiconductor Field-Effect Transistor

MPPT Maximum Power Point Tracking

MSL Microelectronic Systems Laboratory

NASA National Aeronautics and Space Administration

OCP Open Compute Project

OHSA Occupational Health and Safety Act

PCB Printed Circuit Board

PPE Personal Protective Equipment

PV photovoltaic

RJ-45 Registered Jack Type 45

rPi Raspberry Pi

RS-232 Electronic Industries Association Standard RS-232 Communication Standard

SA South Africa

SLOC Software Lines of Code

SPI Serial Peripheral Interface

SSBC Small Single Board Computer

SUN Stellenbosch University

TO-220 Transistor Outline Type 220

TQFP Thin Quad Flat Pack

UK United Kingdom

USA United States of America

USB Universal Serial Bus

VBA Visual Basic for Application

Wi-Fi Wireless Local Area Network

Chapter 1

Introduction

> *"Too much use is made of mathematics as a training of the mind, and too little attention is given to its practical utility. The method commonly employed for teaching young people mathematics is not unlike that of teaching [them] the motions of the arms and legs employed in swimming before [they have] ever seen the water, or gathered that there can be any use in swimming."*
>
> *– Professors Ayrton and Perry (1882)[Ayrton and Perry, 1882]*
> *Speaking on the education of engineers.*

1.1 Background

How do you educate students in the practical aspects of engineering? How do you know you are teaching them correctly? Can you be sure that you are teaching the material *within the necessary context*, and in such a way that the students are able to make the material their own, to truly understand the principles of what they are doing?

We define engineering as an applied science. Engineering enables humanity as a whole to reap the benefits of scientific discovery through ingenious and creative application of scientific and mathematical knowledge to real-world technical challenges. A vital component of this endeavour is the ability of the engineer to apply learned scientific theory in a practical way that works as effective, efficient, and safe as possible.

One of the primary ways of ensuring that engineering students are able to consolidate theory and practice is through experimentation — in sessions we call practicals. During a practical students are given a chance to test the theories they have been studying, allowing them to cement their understanding by correlating their predictions with real-world results, and giving them a sense of the non-ideal conditions present in physical systems. By observing the differences between the theoretical predictions and the practical results they develop an understanding of the limitations of the theory, the influence of all the non-ideal effects on the final system, and how these conditions are included in theoretical calculations.

We do the same for simulations. Thanks to the rapid increases in computers' power and affordability the use of simulation systems have become commonplace even in first-year engineering courses. A well designed set of practicals can help the students understand the limitations of simulation, and give them a sense for the type of results they should expect. It should also help them to develop a sensitivity for the constructibility of a solution, since it is possible to design very advanced topologies in a computer program that will be impossible to build, completely impractical, or excessively expensive.

But, are our practicals doing this? The key outcome of a practical is that students must be able to *experiment on their own*. However, is this really happening when a student enters the laboratory? Are the students experimenting with the theory, or do they become so overwhelmed by the equipment and systems in the laboratory that they *only learn to use the experimental set-up rather than the experiment itself*?

The first time we in the Department of Electrical and Electronic Engineering at Stellenbosch University were faced with these questions was when we started to develop a set of practicals for a new module focused on renewable energy — entitled Energy Systems 414 (ES414). This module slots into the final year of our four-year Electrical and Electronic Engineering degree programme. It focusses on teaching students the principles of renewable energy systems, with the emphasis primarily on wind, hydro, and solar-photovoltaic (PV) technologies.[Stellenbosch University, 2015]

Our specific focus was on the solar energy component which included new systems that had not been presented previously in any other modules at the department. Our initial goal was simple: develop a set of practicals for solar renewable energy.

Using the available equipment and existing laboratories, we developed practicals that are similar in design to those from other modules in the department in terms of the equipment and methods used. We introduced a few novel concepts, but the majority of the practical followed the way most practicals at the department were presented at the time.

However, during development we were already struggling with the limitations of the laboratory. When we started presenting the module we found that the practical equipment, consisting of various power meters and computers, was not performing as it should, and the students were struggling for the wrong reasons.

The first question came up: *Was this an isolated problem*? We started investigating other modules too, first within our research group and then in the department. Through observations as well as staff and student interviews we soon found that the equipment was not performing as expected and that students were not getting the experience we thought.

Since the problem was not isolated we started by investigating the solutions currently employed in the rest of the department. We found a mix of self-designed and commercially purchased equipment. Buying the equipment seems the simplest solution so we started by looking at commercially available equipment. Unfortunately, despite several benefits, the equipment as a whole did not meet our requirements for several reasons. The three biggest concerns were that the equipment was not designed for the education environment, had proprietary interfaces and was expensive.

Since commercially available equipment could not meet our requirements, we set out to design new systems that could. We initially approached the problem thinking it would be a simple, albeit difficult, electronic engineering design problem. However, as we started planning, it became apparent that there is a lot we would have to understand in order to design a system able to meet our needs. The seemingly simple task turned out to be much harder and more complex than we initially anticipated. Indeed, to realise such a system would require a vast array of knowledge and skills, from a thorough understanding of engineering to psychology, industrial design, systems theory even law.

But more than that you also require a detailed understanding of the institution where the educational offering is presented, including the institution's strengths and weaknesses, aims and directives, as well as the culture present in both the student body as well as the staff. The system, however technical in nature, cannot be developed in isolation from the people who will be using it and we must be sensitive to all the stakeholder needs.

In short, this is an endeavour that cannot be effectively resolved within a single research project, or by a single person or group, and nor should it be. It is not simply a matter of design and synthesis, but also of ownership and involvement. There is a global shift towards opening information to everyone. The open-source movement, specifically a project like Linux, has successfully demonstrated that by spreading development to the many you are able to build effective and efficient systems that far exceed what could have been contributed by only a few. This is beneficial to everybody involved, even though it means not having sole ownership of the intellectual property.

In a white paper by The Linux Foundation, published in 2008, they try to estimate the total development costs of Linux had it not been built using an open-source, free-development model. [McPherson et al., 2008] According to the report, at least "a thousand developers from over a hundred companies contribute to every kernel release". To determine the value of the software they looked at the Software Lines of Code (SLOC), a method developed by David A. Wheeler. [Wheeler, 2011] In 2008 *Fedora 9*, the reference distribution of Linux used in the study, contained 204,500,946 SLOC resulting in a total estimated development cost of US$ 10.7 billion. To put this into perspective, Apple Inc. (AAPL) in December 2008 was worth US$ 20 billion[1][Yahoo! Finance, 2015], so Linux's development cost would have been equal to about 53% of Apple's book value at that time.

And the open-source movement did not remain isolated to software. In April 2011 Facebook announced the Open Compute Project (OCP), an initiative that saw them completely opening up the technology that runs their data centres. By March 2015 the member organisations included Facebook, Intel, AMD, HP, Dell, Apple, Cisco, and Microsoft.[Frankovsky, 2015][The Open Compute Project, 2015] The progress has been phenomenal. By 2015 the project has been able to open up almost every aspect of the data centre, from motherboards to racks, cooling systems and even the network infrastructure. It is estimated that the OCP has saved Facebook more than two billion US$, and cut business such as Fidelity Investments's data centre bill by 20%.[Bort, 2014]

For us this is a clear indication that a system developed by a community is not only a good idea, but a feasible one. But, it would need a steering group to ensure that the standards and interfaces allow the various pieces to mesh together, and to enforce a standard of quality that ensures the trustworthiness of such a system. A framework would need to be developed.

A framework would provide a clear vision for the project, outlining the requirements and goals in such a way that it steers the project whilst still allowing for the creativity and freedom of the members to innovate — contributing to the growth and development of the whole system.

But the development of such a comprehensive framework requires an understanding of the field of engineering education research, as well as a detailed study of the specific problem of equipment and systems design for practical engineering education. This study seeks to introduce engineering researchers to the field of engineering education research, familiarising them with the current approaches and discourse. It is also a first look at the specific problem of practical engineering education, seeking to identify the various aspects that will need to be addressed when the framework itself is developed.

By thoroughly understanding all the aspects of the problem, and knowing which problems to pay specific attention to, we hope to start the process of developing a system that not only serves as excellent laboratory equipment, but as a powerful didactic tool.

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[1] 236,606,600 shares at a closing price of US$ 85.35 on 1 December 2008.

1.2 Problem Statement

To distil all the requirements of a well designed, comprehensive practical system into a set of design specifications is difficult. The field requires a vast array of knowledge and there are a significant number of unknowns. Furthermore, due to the expansive nature of such a system and the desire to provide shared ownership, there is a need to develop the system in collaboration with other individuals and groups.

Finally, considering the aim of achieving a sustainable project, there is a need to understand all the problems in such a way that the eventual framework is able to set realistic and practical goals and development guidelines.

1.3 Research Objective

Our objective was to investigate the current state of engineering practical education as well as the requirements, limitations and challenges that face the development of a new system. To get an indication of systems requirements we take a look at current literature, evaluate available systems currently employed on the market, observe current educational offerings, conduct staff and student interviews on experiences of current learning initiatives and develop a series of prototypes.

We propose the following hypothesis: *It is possible to distill the requirements of a system that would be able to meet the needs of the modern laboratory into a framework that will guide development, thus allowing for continuous improvement and lowering costs, without compromising quality or safety.*

1.4 Summary

How did modern engineering education originate, and what have been the driving factors in the development of the field as we know it today? How did the accreditation standards come about and how do they ensure the application of uniform levels of quality across countries and continents? The literature review in **Chapter 2** starts with these questions. We proceed to investigate advances, the current and future trends, as well as criticisms of the current state of engineering education research and engineering education as a whole. We also take a look at research initiatives investigating the design of new practical education systems, focussing on several projects, and we discuss various approaches to the problem.

With the theoretical background established, we move on to **Chapter 3** where we study the current practical engineering education offerings, using our department as the basis for our study. We start by examining the perceptions and experiences that both students and staff have with current practical education. Then we make a brief study of the current educational offering across the entire four-year degree program. Finally we make detailed observations in practical sessions as they are presented now, and tie this into the development of the practicals themselves, as well as the experiences gained by presenting ES414 from 2012 to 2014.

Next we take a look at some considerations that must be made during the development of a new system for practical engineering education. **Chapter 4** identifies the various factors and agents that have an influence on, and a stake in, the practical education system. From this identification we proceed to address the various aspects that provide boundaries to the development of the final system. We discuss the importance of shared development as well as a continuous improvement methodology to ensure the sustainability of the designed system. The idea of a tailored system for each user group is introduced as well as several other topics on, amongst others, the use of these systems in examination.

Chapter 5 starts investigating the design of the equipment and system itself. Using the solar energy practicals of ES414 as an example, we determine a broad set of requirements and using soft-prototyping techniques we start to develop a series of prototypes based on these requirements. The soft-prototyping techniques stop short of developing physical bench ready systems, making it very inexpensive, but still yielding good results and allowing us to develop frequently and often. With each prototype both the requirements and the design are changed, and the chapter culminates in the outline of the third and final prototype developed in this study.

The next three chapters discuss elements of the third and final prototype. **Chapter 6** details the *inter-module communication interface*, a key feature of the system that allows the various modules to interact with each other to easily create combined systems.

Chapter 7 focusses on the hardware of the third prototype, developing some of the various sub-systems used in the design. The main aim of this chapter is to determine the challenges faced by the electronic design. Because of our very constrained development budget, roughly 10,000 South African Rand (about US$ 800), we have not been able to build the complete system we designed, instead focussing on the implementation of key elements to understand the challenges posed by the hardware itself.

In **Chapter 8** we take a brief look at the software front-end of the proposed system, discussing ideas, possible constraints and considerations for the design of the software in order to allow it to function as an interface to the equipment.

Finally in **Chapter 9** we briefly summarise the work presented as well as the contributions made and provide recommendations for future work.

Chapter 2

Literary Background

> *"Designers often think of themselves as typical users. After all, they are people too, and they are often users of their own designs. Why don't they notice, why don't they have the same problems as the rest of us? The designers I have spoken with are thoughtful, concerned people. They do want to do things properly. Why, then, are so many failing? All of us develop an everyday psychology — professionals call it 'folk psychology' or, sometimes, 'naive psychology' — and it can be as erroneous and misleading as the naive physics [of Aristotle who observed and tried to explain physical effects without understanding all the forces involved, resulting in a lot of mistakes.]"*
>
> *– Donald A. Norman[Norman, 2002]*
> *The Design of Everyday Things*

2.1 Introduction

As a designer you have to be very careful that what you *think you know* is in fact useful knowledge and not simply assumptions and prejudiced masquerading as such. As qualified engineers, we have been educated in an engineering programme, which followed on years of schooling. This means that our view of education is necessarily one of an insider. The danger of this is that although we are trying to be as objective as possible, it is very often difficult to separate our *opinions* from *the facts* when it concerns education research — considering that we have been educated within the milieu of the very system that we are now examining and criticizing.

This separation of opinion and fact is possible, it is just difficult, and thus it is crucial that we not only examine practical engineering education itself, but also our *methods* for examining it. An important aspect of this is to identify and declare our assumptions and the conditions of our study. This will allow us, as well as other researchers, a better understanding of our perspectives and reasoning. One key condition is that we are in South Africa (SA). As a developing nation, our priorities in terms of education, as well as the state of prosperity of our students and institutions, are very different from those of developed nations such as the United States of America (USA), the United Kingdom (UK) and Australia.

But, despite different priorities, in terms of engineering at least, SA and these developed nations have a shared standard of education. This is formalised as the Washington Accord, a multilateral accreditation agreement which compels signatory nations to uphold a set of standards within their own accreditation authorities. These local authorities are evaluated every six years, and they in turn provide accreditation evaluation and authorisation to the local engineering schools, ensuring that engineers trained at these schools have engineering degrees that meet the standards of the accord. This is beneficial since these accredited engineers will have their degrees recognised by the other signatory countries, and vice versa.[International Engineering Alliance, 2014]

But how did this multinational agreement come about? Considering that all 17 signatory countries of the accord have a shared standard for engineering education, it must therefore mean that they also have similar pedagogical approaches. But what are these and how did they develop? We start our investigation by looking back at the development of engineering training in the USA.

2.2 A Brief History of Engineering Education

The first time engineering education was formally assessed in the United States of America was in 1918 with the publication of "A Study of Engineering Education" by Charles Mann — commonly referred to as the Mann Report. [Mann, 1918]

The majority of engineering schools in the USA were founded around 50 years before the Mann Report, and it is this period that Mann and his committee concentrated on. Initially there was a pedagogic consistency on education amongst the institutions, having four year programmes[1] focussing their first two years on what can be called the *fundamental sciences* and the last two years on *the application of these learned sciences to problem solving.* However, by the time of the Mann Report, this focus had shifted. Primarily to cater to industry that increasingly wanted to apply the knowledge of science to their operations, courses had started introducing *special studies* that would allow the students to be proficient at the techniques used in factories and other industries when they graduated.

But the result of this focus was not necessarily a good thing. Mann noted: "As a result [of the focus on speciality studies], the load upon the student has become

[1] A programme length that has persisted to this day.

continually heavier and bears unequally in different places and in different parts of the course. In addition there is a wide spread[sic] feeling that under this pressure the great body of students fail to gain, on the one hand, a satisfactory grounding in the fundamental sciences; and on the other hand, do not fulfil the expectations of engineers and manufacturers in dealing with the practical problems with which they are confronted on leaving the engineering schools."

This excessive focus on speciality training gave rise to the Committee of the Engineering Societies (CES), and the commissioning by the group of the Mann Report. The CES grew from a need to study engineering education, and help guide its future, and at the time of its founding included the American Chemical Society, the American Institute of Chemical Engineers, the American Institute of Electrical Engineers [2], the American Institute of Mining Engineers, the American Society of Civil Engineering, the American Society of Mechanical Engineering, the Society for Promotion of Engineering Education.

The purpose of the Mann committee was not to examine the current state of education at the time, although they did visit several schools as case studies, but rather to examine the fundamental question of how students *should* be prepared for the engineering profession. To do this they considered, like we do in this study, the view of the teacher, the engineer, the manufacturer, and the employer. The only difference is that we also take the view of the student into account. And, although the roles and scope-of-work of these agents have changed over time, there is still much that can be gained from the Mann Report.

Engineering training was not always offered in the USA. We start by examining the introduction of engineering there. We feel it apt that the history of engineering education in the USA, as the major driving force behind the standardization of modern engineering and engineering education, forms the basis of our discussion.

In the USA[3], as in many countries, engineering started with the army engineers. At the time of the War of Independence (more commonly known as the American Revolution) in 1775, no engineers were being trained specifically in what we know today as the United States. There were American engineers, but they were mostly self-taught through reading, or they trained by serving under British engineers in previous wars. Two months after the War of Independence started Congress established the Continental Army, and assigned General George Washington as Commander and Chief. [Walker, 1981]

As Commander and Chief, his first concerns were to strengthen his army, and ensure that the British forces were kept in Boston. This required earthworks to ensure outposts could be set up to monitor troop movements. But Washington

[2]The AIEE and the Institute of Radio Engineers, founded in 1912, merged in 1963 to form the current Institute of Electrical and Electronics Engineers (IEEE).[Institute of Electrical and Electronics Engineers, 2015]

[3]We use the term USA for simplicity, using it to refer to the country even before it was unified.

lacked the engineers required for this. To the US congress he complained that "The Skill of those engineers we have ... [is] very imperfect and confined to the mere manual exercise of cannon, whereas the war in which we are engaged, requires a Knowledge comprehending the Duties of the Field and Fortifications."

Unfortunately the first officer appointed as Chief Engineer, Col. Richard Gridley, would not be able to provide him the support he wanted. Later on another engineer, Lt. Col. Rufus Putnam, joined and despite feeling that he was himself not fully qualified for the job, ended up providing invaluable advice to Washington. Regardless, as the country started to realise the imminent threat of war and the need to shore up defences, they would need many more engineers.

Washington, the Congress and the Army's chief engineer, all realised that without experience these self-taught engineers could not provide the support needed. And since engineers require extensive training, which was (as it still is) a slow and costly process, they were essentially stuck.

The degree to which the lack of engineers influenced the country was highlighted as the states started to become desperate for engineering support, not only for war support but also for several large civil projects. Some states obtained civilian engineers, but not enough for the work that needed to be completed. The states pressured the army, believing that it *should* provide the engineers. Washington, however, could not allow this and the situation became so bad that the states started using under-qualified and inexperienced engineers, with Maryland's Charles Carroll commenting that "We [the states] must ... avail ourselves of the skill of such [engineers] as we can meet with among ourselves, though their *Knowledge be not so perfect or complete*[emphasis added]".

Some of these problems remain today, even if it is not in preparation for war. The training of engineers is more than an education provided at a university. The field of engineering is a complex blend of a university education and, on the other hand, an industry of professionals to support new candidates in their professional development. If the training of engineers is interrupted, or slowed, it has knock-on effects on many facets of society and, worse still, can only be remedied with time. Although funds for education play a vital part, it is not the primary requirement as lost expertise is very hard to recuperate.

In 1775, as the American colonies realised that reconciliation with Britain was no longer possible, they started to focus on the training of their own engineers. Congress directed Silas Deane, an ex-congressman from Connecticut, to visit France — Britain's most powerful enemy and, more importantly, the centre of technical education in Europe. One of Deane's tasks was to recruit engineers, most famously from the *Ecole du Corps Royale du Genie*, or School of the Royal Engineers, which had a an engineering program that *combined theoretical knowledge with practical education.*

After the war, Britain sought to crush the new colonies, mainly by attempting to undersell them. America met this threat in three ways, firstly by developing societies to further certain skills and "encourage the spirit of enquiry", secondly by offering premiums from the state treasury for any developments that might be beneficial to the country, and finally by inviting trained artisans to settle in America and thus give her the benefit of their training.[Mann, 1918]

The next great advance came after the War of 1812. Unscientific farming methods had exhausted the soil, resulting in many people moving west to seek new workable land. This resulted in two problems, the need for better training to ensure that the exhausted farms could be reworked to stop them being abandoned, and secondly that better transport, of people to the West and goods back to the East, were required. According to Mann, the growing demand for scientific information to improve production and the little attention paid to it were the defining factors of engineering at that time.

And the limited availability of engineers continued to be a problem. They are those most readily trained in the application of science to the practices of industry, and not having them is a major concern. The situation became so bad that in 1852, a document by the Illinois Industrial League presented to the state legislature stated that between a third and half of all production was lost due to 'worker's ignorance of scientific laws and methods of work'.

As we noted earlier, most USA engineering schools were founded in the 50 years prior to the Mann report. The history and development of these schools are of note, though we will not discuss it in detail here. One element we wish to highlight is the tremendous growth rate. In 1860 only one in every million Americans studied engineering, but 56 years later, in 1916, this number had increased to 43 per million — an exponential growth per decade.

Not only did the number of students entering the programme change, but also the number of those passing. In the 1870s the engineering schools had such a low pass-rate that only one in every ten students finished the engineering degree; although many would go into apprenticeships to become skilled in technical crafts. By 1918 this had increased to 40% and by 2012 the pass-rate in the USA had increased to 60.8%. [National Science Board, 2012]

The Mann report started its analysis of how engineering education should be conducted by looking at the aims and curricula of the engineering schools at the time. It is not required for us to go into the detail of this analysis, except to mention that numerous schools had taken inspiration from similar institutions in Europe and Britain. The institutions also sought to produce students who could grow industry, through development and innovation, not simply reduce losses.

For our study this report gives an indication of the type of approach followed in the development of a new system for engineering education. Although we are not reworking engineering education as a whole, it is none the less important to note how the developments in engineering education were continuously shaped by a strong desire and need for an improved livelihood. Over the century since 1918 engineering education would keep developing. Froyd, et al, summarises some of these developments into five major changes, and starts with the introduction of **Engineering Science and Analyticity Emphasis** and the use of **outcomes-based accreditation**. [Froyd et al., 2012]

According to Froyd, et al, the first change in the content of (what we refer to as) the modern engineering curriculum, came about in 1935-1965 when universities such as Stanford started doing away with the more hands-on programme, which prioritised machine shop, surveying and drawing classes to focus more on science and mathematics courses. In May 1952 the president of the American Society for Engineering Education, S.C. Hollister, appointed a Committee on Evaluation of Engineering Education, headed by Prof. L.E. Grinter. They compiled a report, commonly known as the Grinter Report, which provided the first analysis of engineering education in the USA following the two world wars.[Grinter, 1955]

The Grinter Committee was tasked specifically to clarify the curriculum content that differentiates engineering education from the education in science on the one hand, and *subprofessional*[4] technology on the other. The committee enlisted the help of 122 institutions throughout the USA. The results were published in a preliminary report that the committee considered to be widely successful due to the immediate interest, discussion and feedback from the education community.

Based on comments on the preliminary publication the committee brought on two changes when they published the final document. The first was a discussion on the *graduate phase of engineering*, which would only receive proper attention in a future report. The second was based on feedback, particularly from industry, that sought to place greater emphases on *the inability of engineers to express themselves in clear, concise, effective, and interesting language.*

The Grinter Report also proposed specific ideas about the type of staff that must be employed by an engineering school. There is a great sense of focus on the teacher as someone who is creative, inspiring, and able to meet the minds of the students. The report emphasises that a faculty staff member "should perform creative work whether it be in teaching, writing, research or professional activities."

Given that the curriculum was constantly under development, a need arose to ensure that the various institutions were all training engineers to a specific standard. In 1932 the Engineers' Council for Professional Development (ECPD) was founded by seven engineering societies, and tasked with the education, ac-

[4] In this context *subprofessional* refers to technical staff that perform their duties above clerical level, but still under supervision of a professional.

creditation, regulation and professional development of engineering professionals and students in the United States. [Accreditation Board for Engineering and Technology, 2015] The organisation was renamed in 1980 to its current title of *Accreditation Board for Engineering and Technology (ABET).*

ABET, and the ECPD before it, oversaw engineering accreditation in the USA from its inception. However, the accreditation system was frustrating to the engineering schools, as it had many problems. According to Prados, et al, "as the number of accreditation visits multiplied and, in the litigious atmosphere of the late twentieth century, the prospect of legal challenges [against ABET itself] to unfavorable accreditation decisions increased, ABET review criteria became more quantitatively focused and less dependent on professional judgement."[Prados et al., 2005] The relationship between ABET and the engineering schools became "adversarial and [at] arms-length." It is clear that there was a breakdown in trust between the accrediting organisation and the institutions providing the learning, as Prados, et al., points out "[the review] criteria were increasingly prescriptive — from less than one page of general criteria in 1959 to more than 19 pages of smaller type in 1999."

This type of limitation evoked strong reactions from academia, with "President James J. Duderstadt of the University of Michigan and President Charles M. Vest of the Massachusetts Institute of Technology, both engineers, [stating] publicly that engineering education must change significantly to support the new quality-oriented environment and that ABET's rigid, bean-counting implementation of the accreditation criteria created a significant barrier to needed innovations in engineering education."[Froyd et al., 2012]

The criticism were heard, and in 2000 ABET responded by introducing a new system for engineering accreditation, an outcomes-based approach to accreditation, designated *Engineering Criteria 2000 (EC 2000).* This model took nearly ten years to develop and implement[Prados et al., 2005] and focusses on a set of 11 student outcome criteria. Each institution is visited every couple of years by an ABET team, and during these accreditation visits the institution must show documented evidence of the way in which each outcome is addressed. It is not prescribed how the specific outcome criteria must be taught, or how it must be assessed by the institution, but simply that it must be clear that the students have been prepared on each outcome, and that the institution must have documented to demonstrate that the program prepares graduates to attain the education objectives.[ABET, 2015] According to the 2014-2015 revision of the ABET accreditation criteria, the student outcomes are:

1. an ability to apply knowledge of mathematics, science, and engineering;
2. an ability to design and conduct experiments, as well as to analyse and

interpret data;

3. an ability to design a system, component or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability;
4. an ability to function on multidisciplinary teams;
5. an ability to identify, formulate and solve engineering problems;
6. an understanding of professional and ethical responsibility;
7. an ability to communicate effectively;
8. the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental and societal context;
9. a recognition of the need for, and an ability to engage in, life-long learning;
10. a knowledge of contemporary issues;
11. and an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Other authorising organisations have followed a similar road. The Engineering Council of South Africa (ECSA) has a similar outcomes based approach to engineering education accreditation in South Africa, and identifies its own list of student outcomes which, although not an item-for-item match, reaches the same principles and goals as those of ABET.[Engineering Council of South Africa, 2004]

The standards also address other aspects of engineering education, and although not expressly limiting a specific action, it provides guidelines. For example, in reference to the earlier problem of premature overspecialisation in the engineering degree, the ECSA accreditation standard notes that "BSc(Eng)/BEng/BIng programmes should not address narrow niche markets". The principle it enforces is that the wide base provided by accredited degree programmes must provide a starting point, since engineering education should be a life-long learning endeavour "... [allowing] maximum flexibility and mobility for the holder [of a degree] to adjust to changing needs".

This brings us to the current state of engineering education. Engineering is a global endeavour, with changing requirements worldwide, and a shifting need for engineers. Accordingly the accreditation organisations are no longer isolated, rather ABET, as the accreditation authority of the USA, ECSA as the counterpart in South Africa, along with 15 other nations, are cosignatories of the Washington Accord — ABET in the initial phase and South Africa during the Initial Expansion phase ten years later in 1999. [International Engineering Alliance, 2014]

As discussed earlier, this multilateral accreditation agreement compels signatory countries to uphold a set of accreditation standards agreed upon by all the signatories. This helps ensure an international standard on engineering education through requirement setting, allowing a country to benefit from a global standard and ensuring that it can use engineers from other countries, as well as have more confidence in the products and services developed and provided by engineers in those countries.

But does this standard truly translate into a uniform standard of education? Our specific interest is in the development of engineering practicals, a field that is heavily dependent on laboratories and equipment. We are interested in developing a system that could benefit students from developed and developing nations equally. What are the best ways to bring this about? And how will we measure the efficacy of any endeavours?

The engineering laboratory, including the introduction of new concepts on remote laboratories, have developed significantly. But, regardless of the form, one of the major drivers of engineering education, specifically in the laboratory, is the technology powering it. We discuss this next in more detail.

2.3 The Influence of Technology on Engineering Education

It should be fairly obvious to any person currently working in engineering, be it at a university or in industry, that the rapid pace of technological development has had an incredible impact on the way we live our lives and do our work every day. Computers, the internet and the general progression of technology have allowed people to connect and have dramatically shrunk the world, whilst at the same time increasing its complexity considerably.

One of the most critical changes, however, is how ubiquitous computers have become, and how their roles have shifted from being a resource used for business or research to a device for everyday life. The separation between personal and professional, on the computer at least, has started to disappear. And the interface with a person's everyday life is also changing.

The biggest effect of this change for us in a university context is that personal computers, phones and tablets are now with students wherever they go. They take notes on it, keep textbooks on it, make voice and video notes, and in some cases have the simulation software and programming languages running in class. Whether the availability of computers in the class context is good or bad is, in our opinion, irrelevant. It is the situation as it is, and attempting to change it would be fighting an uphill (and pointless) battle. Rather, our discussion is on how to use the computer to maximum benefit. It remains a tool, and tools, even excellent ones, used in the wrong way can be very detrimental.

In 1958 an Italian author, Simon Ramo, published an article in which he laments the waste of teachers' time. What was needed, he said, was a system where "...fewer skilled teachers [are] being wasted in the more routine tasks that a machine should do for them."[Ramo, 1958] Although some have stated that he was predicting the computer, we think he was merely expressing exasperation about the fact that teachers could do much more with their time, rather than repeating mundane tasks that do not require the insights and skills of a teacher — most notably the marking of exams.

Overwhelmingly the use of computers to phase out mundane tasks can be seen as a good thing, but there is a caveat: *If an education task can be completely replaced by a computer, is it in fact a task worth having?* This is a question that interests us. If one could build a machine to replace certain aspects of our current practical engineering education programme, should those aspects still persist? And should all the tasks currently employed in a practical be kept, replaced or completely removed? Are all the aspects of a practical truly functional, or are some perhaps outdated?

These questions are rooted not only in the everyday administration but especially in the testing and evaluation of student ability. At our own department we have seen the introduction, and eventual failure of systems to mark assessments by computer or, more accurately, to greatly accelerate the marking process. These systems ultimately failed because they did not address the true objectives of the evaluation process, which is to *educate* the student *through feedback*.

Grading is one of the most tedious processes in teaching. Naturally then that people have spent a lot of time investigating systems whereby a computer can do the marking. However, this is where it is very important to ask what the purpose of evaluation is. Much has been written on evaluation, and we will not go into this in detail. The only point we wish to emphasise is that evaluation can be performed for several reasons. In our study the important thing is to separate the evaluation from the system used to perform it, whilst not losing sight of its purpose.

The computer is not only changing how we teach, but also what we teach. Computers in all forms have become increasingly powerful over the last two decades. The high-end scientific calculators, a requirement for engineering study, are capable of over 460 functions, including numerical integration, differentiation, matrix mathematics as well as a host of memory and conversion functions.[Sharp Corporation, 2015]

Students are now able to perform complex numerical integration techniques easily and by themselves, thanks to programs like the commercial mathematics package MathWorks® MATLAB® or free software like SciPy[5]. For example, a final-year module in signal processing will not only cover topics such as the Fast Fourier Transform, but can have the students analyse these, coding and verifying for themselves the different types of algorithms and the effects of the various parameters on the accuracy of different methods — all in one afternoon. (And with Python many of them will run it on their smartphones after the class.)

2.3.1 Simulation

A simulator can be used as both a teaching and a design tool. We are primarily interested in the teaching aspect. Using Smith's description, defining an educational simulator as a "... computer program which incorporates a mathematical or logical model of an engineering system or process, allowing the user to specify the values of one or more system parameters and, following computation, to examine the resulting values of other system parameters. "[Smith and Pollard, 1986] This definition does not make any mention of hardware, mainly because it looks solely at the system driving the virtualization of some physical process. How this model is provided with information, and how it relays information back to the user, is not defined.

A good example of the various input and feedback techniques, is the aircraft flight simulator. In the simplest case the flight simulator runs wholly on the user's computer, with a single screen serving as the view-port and instrument console, and the computer's keyboard and mouse replacing all the controls, as can be seen in the screenshot from Microsoft® Flight Simulator 2012[6] (Figure 2.1a). Everything in this screenshot is visible on only one screen, severely limiting the user's ability to interact with the simulation. Also, since no airplane uses a mouse and keyboard as flight controls the simulator does not provide a good analogue to a real plane. But it provides a functional, and cheap, starting point.

The alternative is a simulator that incorporates a physical control surface, ideally being an exact replica of the system that is being simulated. This allows students to react to the system as they would do in a real-world scenario, but have a computer program simulate the effects of their actions. It is a much better simulation, arguably the best possible alternative to the real thing, but very expensive. The system at the National Aeronautics and Space Administration (NASA) Aviation Systems Division (Figure 2.1b) costs in the order of US$ 5000 per day to use.[Terdiman, 2009]

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[5]The SciPy library is a software library for the Python programming language. According to the development group it "is one of the core packages that make up the SciPy stack. It provides many user-friendly and efficient numerical routines such as routines for numerical integration and optimization."[SciPy Developers, 2015]

[6]Microsoft, Encarta, MSN, and Windows are either registered trademarks or trademarks of Microsoft Corporation in the United States and/or other countries.

(a) Screenshot from Microsoft® Flight Simulator 2012. (Used with permission from Microsoft.)

(b) NASA Flight Simulator (Image courtesy of NASA Simulation Laboratories: Aviation Systems Division.)

Figure 2.1: Simulators of different complexities.

As the price and complexity increases, so too does the realism of the simulator, and the subsequent learning, by allowing students to familiarise themselves with the system they will be using. It also allows students the unique opportunity to run and rerun various scenarios that are both challenging and rare, possibly only occurring once in a lifetime (if ever) in the field. Thus, a student pilot can learn to fly under emergency conditions, an engineering student can learn to operate a power plant and a medical student can learn to do complex surgery, all without risk and at much lower costs compared to the alternative.

There are two main reasons for using a simulator as an alternative to the real thing, namely the risk and cost involved. Other reasons mainly stem from these factors. For example, you can leave a simulator open for use 24-hours of the day without risking the safety of the students, something that cannot be done in a high-power machine laboratory.

But, what do simulators teach students? In the case of the flight simulator, it teaches the action of flying but not the underlying operations. Engineering, especially at university level, should not be overly concerned with the operating of systems, but should rather ensure that students understand the underlying principles — at least, that is what can be seen in the accrediting standards. The key is experimentation and measurement. Students must not only perform experiments, but learn how to set them up. If they do not, the technique of fixing variables to isolate a specific parameter will be lost on them.

There are many ways to make simulation more effective. Feisel argues that the inclusion of more accurate models, as well as statistical fluctuations to the results, can create a more realistic simulation environment.[Feisel and Rosa, 2005] And Balamuralithara, et al., note their experience with a simulation system which, though not providing the “real environment” experience perfectly, was still able to help students due to several advantages over the physical laboratory, most notably the flexibility, more thorough explanation of the concepts and repetition.[Balamuralithara and Woods, 2009]

But, what if, instead of a simulation, one uses a physical laboratory but enables it to be operated and observed remotely. The idea of a remote laboratory was first touched on by Aktan, et al., in 1996 in a paper entitled "*Distance Learning Applied to Control Engineering Laboratories*". The authors discuss a system they developed at Oregon State University that would allow students to use a control systems practical remotely and in real time.[Aktan et al., 1996] They identified active learning, data collection and safety as the three properties that a remote laboratory should have.

The remote laboratory is an extension of the functions of a real one. We have looked at the role of experimentation and simulation in literature, and in Chapter 3 we will also look more closely at the current systems used at our own department through observations and interviews. But, first we delve deeper into the ideas on remote laboratories presented in literature.

2.4 The Remote Laboratory

Although we do not intend to develop a dedicated remote laboratory, it is still useful to look at the developments in this field. What, if any, are the benefits of a remote laboratory? In a 2003 paper Rohrig, et al., highlights the fact that remote laboratories have no limitations on when the student is able to perform the practical tasks, thus allowing the practicals to be scheduled more effectively and in-line with the material as it is taught.[Rohrig and Bischoff, 2003] Furthermore, since the student does not need to be in the laboratory, universities can share resources.

To enhance the experience, Rohrig, et al., used a 3D chat environment to give the students a sense of working together with each other in virtual space and the authors argue that this would help to transfer the concept of collaborative learning into this online medium. We feel that this may not really be required, and considering the additional network bandwidth required, might worsen the experience.

Another development came from Deniz, et al, who introduced the system as a "Web Application Service running over a special piece of software called a Web-Kernel". This essentially meant that their laboratory ran completely on the host machine, serving the content to the user via their web-browser — thus promoting a traditional server-terminal approach.[Deniz et al., 2003]

The development costs of a remote laboratory was investigated by Lowe, et al., in 2012. They did a literature review to investigate how authors reported and used the cost of remote laboratories in publication, and found that 68% ($N = 50$)

of papers used cost as a rationale for the use of remote laboratories, 24% made no mention of the costs, and the final 8% were papers wholly dedicated to discussing the costs.[Lowe et al., 2012] They designed a model for the development of a remote laboratory based on the one that they had built at their university, and we will briefly touch on this again later. We now simply wish to highlight the development costs, which they estimated at US$ 67,000[7].

In Australia universities share remote laboratories. Their national consortium, LabShare, is an initiative to share the remote resources of the various universities. Lindsay, et al, introduce the tools available to members of the consortium, specifically the unification of terms amongst members, as well as tools for the design of lesson plans, frameworks for rig stability, etc.[Lindsay et al., 2011] However, the guidelines provided, at least those addressed in this article, are very limited in scope.

In a 2011 report, entitled *The National Engineering Laboratory Survey: A Review of the Delivery of Practical Laboratory Education in Australian Undergraduate Engineering Programs*, the researchers compared the traditional hands-on laboratory with the remote one by surveying staff and students at several universities in Australia.[Kostulski and Murray, 2010] The survey confirms many of the opinions we have expressed thus far, but there are two slightly unexpected results. Firstly, looking at the laboratories from a student perspective 48% ($N = 134$) of executive, academic and technical staff agreed that hands-on laboratories provide a better, or far superior, "overall satisfaction" than using the remote laboratories. Secondly, 48% ($N = 151$) of those in the three staff groups felt that both laboratory types provided the same learning outcomes, 45% said that hands-on laboratories provided better or far superior outcomes and only 7% felt that the remote laboratories do.

2.5 Chapter Summary

This chapter provided an overview of the history and the current state of engineering education, as well as a review of the literature and developments in the field. Through this we saw the development of engineering education as a field and, specifically for us, the focus on combining practical teaching with theoretical knowledge.

Also, we see the interaction between engineering and industry. By the turn of the previous century the various engineering schools were already struggling to find a balance with industry in the training of engineers, which hinged on the readiness of engineers when they leave the engineering schools, versus the training of independent scholars able to learn on their own and adapt, even if this meant

[7]Using the 2012 exchange rate average of US$ 1.03083 to AU$.

that more training was required after they graduated. Industry wanted engineers trained in their specific fields, but the accreditation standards won out, ensuring a more broad training spectrum. How to address this remains an active debate.

In the next chapter we will start to investigate the practical educational offering that is currently provided at our department. We will follow on that by identifying aspects that hinder or limit the design, and ultimately combine the contents of this chapter with the experiences gained and the limitations identified to designing the three prototypes.

Chapter 3

Interviews and Observations on Current Systems

3.1 Introduction

Practical engineering education, as we have seen so far, is a complex issue. Up to now we have considered the academic literature, which addresses the purpose of practical education in a general sense, with some focus on its implementation in administrations and accreditation standards. Next we wish to look at the role of practical education in practice and how it forms part of a university's academic offering.

In this chapter we investigate these aspects — using our department's practicals, staff and students as the primary subjects. We use only one university, and though this singular view might be, in some respects, a limitation we are confident that it will still provide meaningful results — primarily because we have limited the scope of the research to only identify crucial aspects of practical education that will inform future decisions on the design, rather than draw general conclusions about all practical engineering education at all universities. As such we feel that our department, at Stellenbosch University (SUN), is as good a starting point as any other; especially considering that ours is a Washington Accord accredited engineering school.

Our starting point is the current attitudes of students and staff to practical education. We were interested in several questions, including how both parties view the aims of practical education, how they perceive its efficacy, and the differences between their views.

Next we conducted observations in the laboratories during practical sessions. We wanted to identify how students use their time during practicals, what they struggle with, their understanding of the work, and especially how they approach problems. As part of these observations we also study the practical laboratory itself, the equipment used, and the problems with using standard commercially available equipment in a teaching environment.

Finally, we discuss our experiences of designing and presenting the practicals for ES414 from 2012 to 2014. As a new module, requiring new content, it provided a unique opportunity to study the presentation of practicals. We take a look at elements that worked as well as those which failed, to provide a platform for the discussion of practical design in general.

The discussions, interviews, observations, and presentation experience together provide guidelines for the development of future systems.

But first, a note on the ethical requirements of the research in this chapter. Since we are working with people (students and staff) we wanted to ensure that we followed strict ethical guidelines to protect all involved parties. The process of obtaining ethical clearance was not familiar to the engineering faculty, and we sought to address this, as engineering education research is inherently a study of people and as such must be approached with sensitivity to ensure no harm is caused to participants, either directly or indirectly.

3.1.1 Ethical Clearance and Institutional Permission

During this study we are not concerned with any user metrics other than to identify the current position of the respondent: staff member, student or graduate student. We have redacted names, organisations and any other personal identifiable information from all interviews. The aim of our research is not to single out individual efforts, but rather to understand common goals and requirements, as well as to identify any outlier cases that may need special attention in future designs.

Since the study deals directly with people we conducted a thorough ethical analysis and submitted ethical clearance applications to the University of Stellenbosch's *Central Research Ethics Committee: Human Research (Humaniora)* for review. All applications were successful. The following studies were submitted:

- PCO-M-201304-KA-S-1
- PCO-M-201304-OP-I-1
- PCO-M-201304-OP-IO-1
- PCO-M-201304-OP-IO-2
- PCO-M-201304-SE-O-1

Furthermore, since the respondents were members of the university, it is University policy to also obtain Institutional Permission. It ensures that the university's staff and students are not exploited, and that studies have academic merit. This application was also successful.

A brief discussion of each application, as well as all the documentation (as required) for each study, is provided in Addendum B.

3.2 Interviews

When we started addressing the problem of practical education we were inundated with opinions and requests. It was clear that both students and staff were very opinionated about what should be designed, what the crucial components were and what they wanted from their practicals. We wanted to get some order in the chaos, as well as give people a chance to provide input to foster a collaborative spirit from the start. We also wanted to look closely at the comments and opinions and attempt to understand not just what people thought but why they thought the way they did.

For these reasons we conducted interviews with students and staff. We included the technical staff who maintain the laboratories, as well as alumni who have spent time in industry. Furthermore we wanted to see if we could classify the various responses, allowing us to develop requirements according to broader categories rather than simply using individual opinions.

We were concerned that we would inadvertently load our biases onto interviews by being too rigid with the questions. Also, since this was exploratory research where we were not entirely sure about the type of reposes to expect, we decided to use an open format interview style. This meant that we had questions, but make them broad enough to allow the respondents to provide as much information as they wanted. Furthermore, some questions were statements, requiring respondents to critique it, thereby starting a new conversation. Respondents who wanted to explore a particular avenue, were allowed to do so. This resulted in some interviews lasting 20 minutes, and some more than an hour.

Though most of the staff interviews were recorded, we cannot provide complete transcripts, as it would identify each lecturer. Furthermore, interviews conducted with students were not recorded as we found early on that it made them very uncomfortable — and as such we only took notes.

Lastly it is important to note that we are a multilingual university, and for many of our lecturers English is not their first language. To ensure that they could express themselves as best as possible, we did not place any limitations on the language spoken during the interview. So, although all quotes are provided in English, note that many of these were translated from Afrikaans.

3.2.1 The Value of Practicals

Our discussion started by questioning the purpose of practical sessions. Lecturers agree that this can broadly be summarised into three goals, namely to cement theoretical knowledge, to give the student the chance to experiment, and to align the theory with practice. Students however see practicals differently. Though some agree with the broad sentiment of the lecturers, they are slightly more negative about practicals. They view practicals more often than not, as a very time intensive activity that yields few results compared to other teaching environments, and they often leave practicals feeling confused.

But, this is not necessarily true of all practicals. As numerous students were quick to point out there are specific practicals that were of great value to them — pointing out that in each one of these cases a practical had caused them to have a breakthrough with the work, or to put it more colloquially, have an *aha! moment*. Prompting them on the possible reasons for this yielded a range of answers, but two elements stood out — a small and good practical group, and proper preparation.

In the past decade the Engineering Faculty at Stellenbosch University grew by 97%, from 1404 students in 2005 to 2770 in 2014.[Stellenbosch University, 2013] Due to these increasing class sizes, and limited laboratory space, the size of the groups doing practicals have been steadily increasing. Because it is very difficult to find time for all the modules the time per practical is limited. To ensure that all the students get a chance to do a practical, there are two options: more students per bench (group) or a smaller practical that takes less time per student.

Although the large groups are problematic, group-work in itself is not the problem. In fact, it seems that many students are more comfortable doing practicals in groups. Proponents of peer instruction will agree that creating an environment where students are able to teach each other is ideal, as this forces the students to debate through problems. Some students also noted that the groups make them more comfortable learning new tools and techniques, because they do not feel that they are struggling alone. Engineering is a very challenging degree and a student seems to work well when there is a partner to work with.

The lecturers agree with the peer education principle in the laboratory. Several stated that they want the practicals to be an environment where the students discover the material for themselves. A group can encourage this, but, the consensus seems to be that a group of three students is the optimum size. We found this to be true when we observed the students during practicals, but more on that in §3.3.

Preparing for practicals is another key aspect of practicals. It can take many forms, but usually consists of the study of the system to be experimented on, as well as performing some theoretical calculations on the results expected in the experiment. Calculating the expected results, some students point out, is crucial to their understanding of the work. Having worked out for themselves what the values should be and then seeing in the practical how it can differ, makes the work much clearer to them. Students do mention that they often form study groups to do homework, but only to help them if they get stuck to the point where they cannot progress on their own.

Sadly, not all students are motivated enough, though this doesn't necessarily stem from laziness. When asked whether all students are motivated for practicals, one lecturer said: "Some of them are there only because they have to finish it. [Others are less motivated and] fall behind if they are not interested in the module. I find that my module is a bit more mathematical, and a bit more, well challenging[1], so I find that when the students fall behind they start to become less motivated. What I do find is that if they do the practical and they have that *aha! moment*, then you can see it helps them a lot. But, unfortunately they [the students] have to put in some effort to get to that point. Not a lot, they just have to keep up to date with the module and they have to do the [practical] preparation, otherwise they are shooting themselves in the foot."

This advice can, to some degree, also be applied to the lecturers. Practicals are presented by a lecturer and some student assistants, who (at our department) are mostly graduate students doing their master's or doctoral research and are required to support the lecturer during practicals. Lecturers do not choose the assistants and, since graduate students are obligated to assist with between three and five modules during their post-graduate studies, they might not be properly motivated, although their motivation seems to be dependent upon the lecturer. One lecturer questioned about assistants' enthusiasm responded: "Some of them are [enthusiastic]. I have had assistants who were really amazing, and some who were only there because they had to be. Sometimes the assistants end up learning more than the students do, which is probably not a bad thing. I do find that [their willingness] is a function of how much effort you [as the lecturer] put into the module. If you are late [for the practicals], and do not have your administration sorted out, then well, that is how your assistants are going to act [...] if you care, your assistants will care, and if you don't, then they won't either."

The same seems true from the perspective of the assistants. We spoke to several and most of them agreed about the value of assistantship because being required to teach enables one to learn the material differently. However, it takes a lot of time to prepare for practicals, and assistants feel that if a lecturer is unprepared and especially if assistants are not briefed well in advance, they feel lost and unable to contribute during the practical, making it difficult to invest time and effort into that specific module. Most of them also prefer modules that are directly related to their field of study.

[1]It is interesting to note that almost all the lecturers interviewed implied, in some way or another, that each one's particular module was more challenging than the average module.

3.2.2 Students and the Laboratories

Are students getting what they should from the laboratories? Many lecturers and assistants disagree — mainly because they feel that students are not able to use the measurement instruments properly.

One problem is the automation of measurement systems — an advantage to professionals, but not necessarily to students. A lecturer points out that since the *auto-set* button was introduced on the oscilloscope, students seem to be getting progressively worse in their ability to effectively measure even the simplest circuits. This is mainly because the student (wrongly) assumes that the computer can do the measurements without any logical input from the operator, and that the unit can compensate for bad measurement technique. Rather than adjust the oscilloscope manually to find the signal they are looking for, or use the auto-set as a starting point, they will simply engage the function without thought as to what they need as output, or what they expect in terms of signal speed and amplitude.

But, this is endemic of a bigger problem: students struggling to debug their work. A lecturer teaching a senior module notes that "…there is a noticeable decline in the ability of the senior students to debug their work. Some of the better students can debug their work by themselves, but the struggling students cannot figure out for themselves where they have to start checking [their circuits], …they cannot make a plan with it themselves."

Again this comes back to the amount of time students are spending in the laboratory. Speaking to students from various years, there is a marked difference in the amount of time spent in the laboratory. The doctoral candidates and alumni we spoke to were in the laboratories when the faculty still had fewer students, and they had spent much more time in them.

The introduction of computers into the course also seems to have had a marked effect on the time spent in the laboratory. It seems that students now might be spending too much time attempting to simulate the circuits, rather than going into the laboratory earlier in the process to experiment. Naturally, simulation is valuable but the doctoral candidates and the alumni felt that time spent working with components and circuits prepared them better, and that they can perhaps draw even more value from simulation because they understand the real world limitations and behaviours of the components relative to the simulation output.

But, can optimizing the practical environment change this. The lecturers do not think so, at least not without changing the equipment. In each module the equipment is used as much as is possible, given the number of modules and students vying for laboratory time. However, the laboratory is a limited resource and to increase its efficiency and effectiveness requires the redevelopment of equipment, or buying more of it.

And the technical staff agree. They are responsible for the laboratory and its equipment. They ensure that the equipment is maintained and that the laboratory is ready when a practical group arrives. This is increasingly difficult. There is considerably more pressure on the laboratories due to the large class sizes. And, as a technician pointed out, you need down-time on the equipment to perform maintenance, which is very difficult if the laboratory is always busy. This problem is compounded by the complexity of the equipment. The goal is to have equipment that can be replaced with off-the-shelf components. If a piece of equipment has been custom designed, especially if it requires bespoke printed circuit boards, then replacing damaged equipment is a cumbersome and slow process. It also complicates the calibration and servicing processes.

A final point is the current level of contention over the amount of set up work that the students must do themselves for a practical. In the low-voltage laboratories where students work mostly with microelectronics, nothing is set up — they must collect components, build the entire circuit and connect power sources and measurement upon arrival. However, the risk for injury in these laboratories is almost negligible. In the high-power laboratory, where the equipment delivers three-phase, 400 V_{AC}, a mistake can be lethal. Furthermore, a connection error can result in a circuit component exploding, a meter being irreparably damaged and possibly even a fire. We will discuss this in more detail in §3.3.1.

3.2.3 Teaching and the Practicals

One lecturer indicated yet another challenge in presenting practicals: "[During a tutorial[2]], I can, by the second or third time that I receive the same question, stop the entire class, and say: 'Stop where you are, I have identified a problem, something that the majority of you do not understand, so let us address it.'[But in a practical] I cannot do this — especially not in the machine laboratory. I cannot stop the entire class and ask them to quickly pay attention to me, or to come and look at something. Even though I have all the practical equipment at my disposal, I cannot tell the entire class to stop their machines, stop their experiments, stop everything they are busy with, just to show them something on an instrument panel or a data projector. [...] You know you sometimes have a frustrating situation in a practical where you see the same problem, or get asked the same question the eighth time, and still have to explain it with the same amount of energy and enthusiasm that you used to explain it the first time."

The reverse can also be a problem. Sometimes it is very difficult to explain a physical concept during a tutorial or a class. Control systems demonstrations can relatively easily be brought to a class, but the high-power and high-voltage

[2] A tutorial is a session, normally lasting about two and a half hours, where students are presented with a set of problems, and the lecturer and assistants are available to help them solve it.

systems can not. This artificial separation, where the classroom is for teaching theory and the laboratory is for experimenting, is problematic. In another senior module, the lecturer points out, it is difficult to separate the material like this. There are experiments that have to be shown in class and theory that have to be taught in practicals. This resulted in one lecturer almost setting a classroom on fire[3]. Students struggle to hear and see the lecturer during practicals because the laboratory is a noisy, open environment.

3.2.4 Evaluation of the Practicals

There are three major evaluation methods currently used for practicals in our department: marking the preparation work done by the students; marking the results collected by the student during the practical; or marking a comprehensive practical report that the students must prepare after the practical. Sometimes a combination of these are used. There are exceptions, and we also discuss the system we used in ES414 later on in §3.4.

Lecturers agree that students must prepare adequitly for a practical, but even though they want to evaluate the student's preparation before the practical, it is simply not possible due to the large class sizes. One assistant we spoke to co-presents a module to over 240 students, with only three other assistants. With each student's preparation taking ten minutes to mark, longer if meaningful feedback is given to the students on mistakes they have made, this will take ten hours per week per assistant — which is not realistic considering that the assistant is a researcher who has a full project load and, on the other hand, cannot be paid for that additional time.

The second solution, which seems most often employed, is to have students record their practical results on a form resembling a question paper. The form details each experiment, and asks specific questions about it. The students then do measurements and calculations to explain what they observed, and discuss any discrepancies between calculated and measured values. They submit the form when the practical ends. To avoid an unmanageable marking workload, students are often paired into groups.

A variation on the last solution is to have the students prepare a formal practical report, outside of the practical. A major benefit of this is that it helps them to develop their technical communication skills too.

Another question we were interested in, was whether a student could pass an examination without attending any practicals? Administratively students cannot, because it is against departmental regulation, but how about practically? One

[3]We feel obligated to note that the students did, in fact, really enjoy this class. The lecturer notes that, of all their work, this class seems to be the one that stuck most in the students' minds.

lecturer points out that for them "... practicals are for support only, and that they duplicate all the results of the practicals in their notes."However, others do set up their question papers specifically to test aspects of the practical environment, because they feel the practicals relate to the way systems are in practice, and want to ensure that the students are able to address this proficiently.

3.3 Observations

In the previous section we investigated what respondents thought; next we want to see what they do, giving us another perspective on engineering practical education. To do this, we decided to observe students, staff and assistants during practical sessions. We wanted to gain an understanding of the problems faced during a practical, and how all the parties responded to it. Also, we wanted to see the type of support the assistants were able to provide, and what the lecturers were doing and how they were dividing their time.

Then there is the laboratory itself. The laboratory with its equipment, management and support staff is effectively another actor in the process. As part of our observations we paid close attention to it; the way students interacted with it, and how functional it was. We also discuss some of the additional equipment available commercially, and comment on the ability of this equipment to function in a teaching environment.

But, how to conduct these observations? We wanted to be as unobtrusive as possible, allowing the students to continue working as they normally would. However, we did not want to use cameras and recording equipment, as we felt this violated the student's right to privacy. We decided that the simplest solution was to join as an assistant on various modules, but only for the practical sessions. We found that the students do not know the assistants well enough to notice additional team members, and those that do, assume that these assistants are specifically there to help with the practical. Two critical conditions of our observations were, first that we do not hinder a student's progress or provide help or advice that we would not otherwise provide and, secondly that we are not interested in or collecting information on a particular student or group of students.

All observations were performed on modules within the Department of Electrical and Electronic Engineering, the majority of which were modules presented by the *Electrical Machines Group* and performed in the *Electrical Machines Laboratory*.

There are three types of laboratories we will discuss here, the Microelectronic Systems Laboratory (MSL), the Electrical Machines Laboratory (Machine Lab) and the High-Voltage Laboratory (HV-Lab). We will focus primarily on the Machines Laboratory, the one most often used for energy systems [4] modules — which were the focus of our interviews and observations.

3.3.1 The Electrical Machines Lab

The Machine Lab is pictured in Figure 3.1. This laboratory has 20 workstations, an example of which can be seen in Figure 3.2. Each workstation is equipped with the following:

- A control board, featuring a
  - Variable output transformer,
  - Three-phase, Wye connected, power supply,
  - Single-phase power supply,
  - High powered DC power supply,
  - Motor protection interlocks
- Motor test-bed, consisting of
  - Two AC induction motors
  - One DC motor
  - on a shared axis.
  - Motor connection panel
  - Tachometer and Torque meter for motor set.
- Oscilloscope
- Small-signal signal generator
- 30 V_{DC} variable power supply

The purpose of this laboratory is to provide an environment where students can experiment with the use of electricity as a means to do work. So, the laboratory is used to study electrical machines, both as generators and as motors, the transmission of power as well as topics in power electronics. Our observations of the laboratory were made during multiple practicals, and while most students attending were studying Electrical and Electronic Engineering, some were from the Mechanical, Mechatronic, and Industrial Engineering departments.

The practicals were mostly focussed on presenting motor theory to the students, including principles of alternating current and direct current machines, synchronous motors and induction motors, as well as the basics of inverter-fed induction machines, single-phase motors and stepper motors. Other topics included

[4] Energy Systems is our department's name for the collection of modules that deal specifically with the use of electricity as a means to transfer energy.

Figure 3.1: The Electrical Machines Laboratory at Stellenbosch University. *(Photo Credit: Author)*

Figure 3.2: A workbench in the Electrical Machines Laboratory at Stellenbosch University. *(Photo Credit: Author)*

transformers, energy transmission as well as various topics on power electronics, such as the design and synthesis of switch-mode converters. [Stellenbosch University, 2015]

A final note on the observations. Since we only have the chance to study a single university, we will not (as discussed earlier) draw any conclusions about this type of education in general. Rather, we use our laboratories, especially problems faced there, to identify possible avenues for improvement.

Control Board Confusion

The bench has a control and connection panel that is situated in front of the students as they work. This panel provides them with various power connections, including three-phase star-connected AC, single phase AC, DC and various others. The panel has a variable transformer that allows one to change the voltage of the AC supply from 0% to 110%.

However, the boards are not performing as required. The board should provide three functions:

- Control of the power supply.
- Connections for the power supply.

- Measurement and indication of the status of the power supply.

Unfortunately, it is not doing this properly. It is clear from observations that students are very confused by the operation of the board. There are several reasons for this, mostly not because of mechanical or electrical restrictions but design problems.

Principle of these is that there is no clear way to "read" the board. By this we mean that when a user is in front of the board, it is not immediately clear where energy enters the board, and where it exits. It is not clear which controls operate which supplies, or how the safety controls tie into the systems.

Compounding the problem is the fact that the board is old, and requires regular maintenance, but without any supports to help technicians do this, such as lamp tests for the panel, or voltage calibration for the on-board meters. The boards also do not follow certain industry standards, such as the colouring standard on three-phase systems, which in South Africa is red, blue and white. Furthermore, the visual alarms are not clear, and safety systems are misused, such as the emergency shut-off switch which is used by most students and assistants as a way to power down the circuit.

Subsequent to these problems we see that most students were not able to use the board correctly, spending an inordinate mount of time during each practical simply trying to get the board working. They would eventually ask the assistants, but the problem is that a large number of assistants cannot operate it either. This is especially true of the safety systems, such as the interlocking mechanism. During most practicals these systems are activated for the students, causing the board to behave differently and leaving them more confused.

In short, the way the board is designed makes it difficult for the student to understand where the power supply ends and the experiment begins. This is further exacerbated by the fact that the metering equipment on the board itself is inaccurate, meant to be used only as an indicator. Thus the experiment has to have several meters just to measure the supply itself, cluttering the desk and resulting in even more confusion.

Problems with Metering Equipment

The laboratory uses professional grade meters for voltage, power and current measurement. The meters provide good readings but are not intuitive, and result in reading errors and equipment damage. The main problem is the way the scale is indicated on the meter, namely nine scales represented in three groups. And although it is fairly simple to read a value, one must check the connections and the dial to ensure that you are in fact reading from the correct scale. On a busy bench, where all the meters look the same, but are measuring on different scales, this becomes a problem.

The meters are also rather sensitive, so the impulse from changing the scale while the meter is in use can cause the meter to either trip, which requires it to be reset, or to blow a fuse that needs replacing. The metering equipment was designed for a professional environment, and is not able to cope with the rigours of a student environment.

This can also be seen in costs. When the department pays for proper and highly accurate equipment the question arises: what is really required?

Circuit Diagram Confusion

The students are provided with a circuit diagram for each experiment, but because much of the equipment is either not labelled, or looks strange and unfamiliar (like the high power variable resistors), the students have a hard time consolidating the diagram with the setup. However, what we saw most often were students who were eager to get the practical done, or simply pressed for time, and rather than mark out the equipment for themselves or ask for advice, simply started.

Some of them used the wrong equipment, took measurements in the wrong places or disconnected equipment that they assumed had been been switched off when in fact it was still live[5].

The same problem occurs with the three electrical machines provided on a test-bed next to each bench. The motors are connected to the bench using a breakout box, where each machine is indicated with an equivalent circuit diagram to mark the connection points. But, since this is connected for the students before the practical starts, they do not understand it, and get confused as to which machine is which, and which one is being powered and which is being measured.

We witnessed a lot of mistakes, and while most were harmless, some were not. In one particular instance a group of students was working with a power-electronic circuit, supplied by the direct-current supply on the workbench. One step of the experiment is to short-circuit the external load resistor to test the unit's load-capacity. The students identified the wrong external resistor, and short-circuited the shunt resistor connected across the direct-current supply, effectively short-circuiting a 200 V_{DC} power-source. The internal protection system then activated, but by that time the power-source had melted because of the resulting short-circuit arc. Nobody was hurt, as most of the equipment is in a protected housing, but an accident like this is a prime example of the danger of not understanding the setup.

[5] These are the only times we interjected with an experiment: any situation where somebody could have been seriously injured.

Safe Operation

It is important to note that, according to the laboratory manager, nobody has been seriously injured in this laboratory in the more than 30 years that it has been operational. The adherence to safety is critical. However, the increasing class sizes make the constant adherence to safety much more difficult. In practicals with small classes, about 25 students, the staff and assistants simply have more time, allowing them to address safety on an individual basis and respond to new risks as they occur. But in the large classes of up to 120 students, this becomes very difficult.

Various elements affect the safety of students in such a laboratory, some obvious and others not. The biggest risk is electrocution. But there are common safety practices to mitigate this risk, the key principles of which are to:

- remove all jewellery,
- ensure that you know the potential of every piece of conductive material,
- only work with one hand at a time,
- and dress appropriately with no loose clothing.

However, as the practical gets busy, the adherence to safety regulations start deteriorating. Larger bench groups are much more dangerous, as we noticed that in most large groups (5-6 people) there were between two and three of the students not paying attention to the experiment, but rather talking amongst themselves or working on other parts of the assignment such as the preparation that should have been completed beforehand, or work that must be completed for the report after the practical. But, they were still standing next to the active equipment, often leaning against the table, or worse, the machine test bed itself where the motor axis is rotating at 1500 revolutions per minute.

It is important to add that these risks must be managed. A laboratory such as this, where line level power is used, provides excellent results, and teaches students to use the equipment safely. The emphasis is on respecting, not fearing, electricity.

3.3.2 The Micro-Electronic Systems Laboratory

The University's MSL is a laboratory used for microelectronics work, including all the microelectronic design modules. The laboratory is well equipped, with each user space having a range of electronic measurement tools, power and signal supplies and a computer. Since the computer is always available students often do computer based work here as well.

There are also a number of demonstration systems — mostly for the Control Systems modules. It is unnecessary to make a detailed observation of this laboratory here, as most of the problems echo those of the Machine Lab. However, we did notice a unique problem with the custom designed demonstration and test gear: the Universal Serial Bus (USB) driver used when the device was built more than a decade ago is now very unstable. But, because it is a proprietary interface, the entire USB system on the demonstration board, as well as the driver on the computer, would have to be rebuilt.

The MSL differs from the Machine Lab on two fronts, namely that it is considerably bigger, and safe enough to allow students 24-hour unsupervised access. This means that practicals performed here are, from our observations, more complicated and more intricate than those in the Machine Lab. Since students can work in the MSL in their own time after-hours, the practicals can have additional sections with challenging questions that require time to do.

3.3.3 Commercially Available Equipment

The equipment available to the laboratories is the same that is used in industry. But, this is not always the most convenient, as professional equipment has a learning requirement, and students who are just starting often seem to be overwhelmed by the various advanced features of the equipment. And it is not only the interface that is the problem, but the functionality itself. Elements of the equipment that are simple to use for experienced users, can be very confusing to the novice. Although the novice must learn about these eventually, there is a balance; novices who are overwhelmed by the system seem to develop a fear of the equipment.

We observed that students, especially from the other departments, who have had less opportunity to use the equipment, could very often not use it to extract the information they needed, and progressed only once the lecturer or an assistant had helped them. Talking to these students later it was clear that they still did not understand how the equipment worked and could sometimes not explain problems in their circuits or observe certain phenomena.

Another problem with this equipment is cost. The equipment in the laboratories was very expensive, since each unit had to perform a range of complicated experiments. Where an engineering design firm might purchase, say, nine regular multimeters and one high-end multimeter, the university has to buy at least ten high-end units, or the practicals have to be designed in such a way that the entire class can use a single unit.

3.4 Energy Systems 414 - 2012 to 2014

We discuss the development and presentation of the practicals for the new module, Energy Systems 414 (ES414), in this section. When the module was introduced we became involved, with the aim to provide a better practical offering as well as study the current solutions and challenges. So we developed a practical offering, and presented that practical for three years, changing elements every year. During this process we made further observations, which we present here as part of this chapter to provide an additional perspective on the challenges faced with practical engineering education.

We start this discussion with a quick overview of the curriculum and our educational objectives. Then we take a look at our approach, followed by a post-mortem of the 2012 presentation of the practical, and a discussion on how we adapted the practicals in 2013 and 2014.

It is important to note that we have the advantage of a very small class, only about 25 students. This allows us to experiment with more time-consuming teaching and assessment strategies, as well as to monitor the individual problems and results more accurately.

3.4.1 The Solar Energy Curriculum

There are several aspects of renewable energy presented in the module, but the two systems focussed on were wind and solar-photovoltaic energy. These technologies were chosen because they contain elements that are familiar to the final year Electrical and Electronic Engineering (E&E) students, such as motors and semiconductor electronics. The aim was to teach them about renewable resources, and the associated power transmission and storage challenges. We argued that teaching the E&E students about, for example, solar thermal systems, would require the introduction of a lot of thermodynamics, thus detracting from teaching about the resource itself.

In our specific section of the work the students were taught about the sun as an energy source, solar photovoltaic panels as a harvesting method, and how this resource fits into both a stand-alone as well as grid tied environment, with and without battery support.

Our section started by introducing the sun as a resource, discussing various factors on the periodicity of the solar cycles, the prediction of insolation[6] using mathematical models, and the effect of single and dual axis trackers. We briefly discuss topics on the solar radiation spectrum, as well as the matched solar photovoltaic panel spectrum.

The next step was to introduce the solar photovoltaic panel itself. Using the second-year semiconductor mechanics as a stepping stone, we discussed the physics of solar photovoltaic technology. In this section of the work we introduced the students to the effects of shading on the panel, as well as the effects of temperature on the operational efficiency of the panels. We also discussed the current-voltage relationship of the panel in detail.

[6]**In**coming **Sol**ar Radi**ation**

The maximum power point, as well as techniques for Maximum Power Point Tracking (MPPT) is introduced next. The students learned about the role of the MPPT in a solar powered system. They were also introduced to various electrical loads, and the responses of these loads to solar systems such as batteries and pumps.

Finally, the students were introduced to the systems perspective, covering the integration of various sources and loads into a single system that is able to perform according to user specification.

3.4.2 Our Approach

We wanted the module to have a strong design component but, more than that, we wanted the students to develop their own tools for completing the design. This gave a central theme to the work of each of the three practical sessions preceding the design project. In each practical specification we highlighted not only the work of the current practical, but also indicated where in the process they are, and how this fits into future work. We referred to this as the *practical roadmap* and provided it in the beginning of each practical document. The roadmap from the 2012 practical is shown in Figure 3.3.

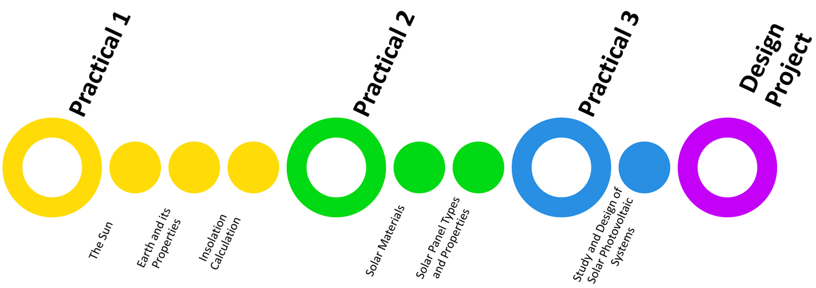


Figure 3.3: *Practical Roadmap* from the 2012 ES414 practicals.

A significant change from other modules is that we did not distinguish between tutorials and practicals. We rather called everything practicals and included problems that traditionally would have been performed in a tutorial, as part of the practical problem set. This did cause some confusion for students, as they were used to a very clear distinction between the two elements, and it quickly became clear that the problem was that students seem to approach practicals rather differently than tutorials — they seem to prepare for tutorials and study them for examinations, but do not prepare nearly as much for practicals.

We also changed the reporting on the practicals. We wanted students to gain experience with technical writing. To this end we required students to write a report on each practical; as if they were reporting the results in a workplace to their immediate supervisor. We explained that the supervisor is a technically competent person, but who has very limited time, so reports can use engineering jargon, but must be concise and immediately identify and clarify any anomalies or unexpected results.

Since the study of renewable energy is a fast-developing field, with a very high level of public interest, we also wanted to develop the students' critical reasoning skills. To this end we assigned an essay that made a specific statement, tasking the student to critique that statement. We thought this the best way to introduce additional reading material and research into the module.

Lastly, we split the class into groups, based on random computer assignment, and then assigned a unique project to each group. This meant that groups could openly discuss their work with other groups, learning from them. It also meant that each group would cover the basic techniques, but would differ in the level of effort spent on the advanced topics. We also made sure to balance the complexity of the projects so that no group was unfairly treated. The final reports could also have been provided as additional study material, again allowing students to learn from each other, with the lecturers' input and corrections.

3.4.3 The Practicals in 2012

There were three practical sessions, plus the design project.

Practical 1

In the first practical the students had to use MathWorks® MATLAB® to build a set of tools that would allow them to calculate all the various parameters associated with the solar resource. This included the insolation at a specific site for various tilt and pitch angles, on a daily, monthly and yearly basis, as well as the effect of single and dual-axis trackers.

The aim of the practical was for the students to become familiar with the calculations and formulas required to make predictions. By programming them into their own tools they had to focus carefully on the constraints of the input values and the limitations of the answers. It also sensitised them to factors such as the differences in the formulas between the northern and southern hemispheres, as well as the effect of certain times of the year on the trigonometric components, which can provide ambiguous results.

This practical was very difficult. We had been assured that the students were capable of using MATLAB®, but they were not. Though they had used it in other modules, and were final year students in a degree programme where they were taught to program, we thought it was reasonable to expect that they would be able to learn to use the software fairly quickly — especially since we did not require complex formulas or nuances of the language. But, observation shows that this was not the case.

The students struggled to program even simple formulas, making common mistakes such as forgetting that MATLAB® uses, for example, radians and not degrees when calculating trigonometric functions. The majority of students also seemed unable to teach themselves; not knowing where to start searching for answers or how to use the built-in help functions.

The result was that the practical took much longer than expected. By the due date many students had progressed, but the code was unstable and in many cases simply not correct. We ended up having to provide solutions so that students could progress to the next practicals.

The lack of programming skills is a big concern for us. There were other elements of the module, namely the MPPT algorithms, that we would also have liked to have the students program and test, but the problem is that we end up teaching programming classes (as indeed we did for some of the students after hours) rather than demonstrating the principles of the work. This is effectively the same problem that we observed in the laboratories (see §3.3.1) where an inability to use the equipment resulted in lost experimentation time.

We made changes to this in the subsequent years (to be discussed in more detail in §3.4.4) but we could not find a solution that would allow the students to start the practical immediately.

Practical 2

This practical is almost similar to the standard laboratory practicals of other modules. During this practical students are given a solar panel and a measurement setup, and are required to make a series of measurements outside in the sun. (This requirement makes scheduling much more difficult, and indeed in 2013 we had to cancel because of rain.) The first group doing the practical can be seen in Figure 3.4.

Figure 3.4: The first group performing the solar energy practical in 2012. *(Photo Credit: Author)*

The students must determine the voltage-current or V-I relationship of the solar panel and compare this to the curve provided by the manufacturer. They must investigate the reduction in power when moving the panel away from its nominal angle and they must determine the effect of shadowing on the panel.

All the experiments are complicated by the fact that the sun moves about 15° per hour, and since such an experiment takes at least thirty minutes, the students must reorient the panel for every measurement, adding a degree of complexity to the measurements.

To measure the loss of power is even more difficult, since the students have to use an external resistor to balance the solar panel onto a specific voltage point, and then measure the corresponding current at that point to get a constant comparable value. This is a laborious and tedious process, but without specific equipment it remains the only solution.

Despite the equipment, the students did fairly well, and from the reports it was clear that most of the topics were well understood. However, elements such as the balancing of the voltage point was not. The equipment still confused the students, and the fact that the equipment was difficult to connect and read in direct sunlight was a problem.

Practical 3

The third practical was on the integration of solar panels, battery storage, grid-connection, stand-alone systems as well as maximum-power point trackers. However, to design experiments on these elements using our equipment soon proved very difficult.

The battery system experiments take too much time, and due to a decision outside our control, the solar energy practicals were scheduled for April and early May, when it is autumn in South Africa, and Stellenbosch is located in a winter rainfall area, where we get fewer sunny days, during this time of year, thus, if we ran an experiment that required battery charging, there was a very real chance that the sun would be obscured and that we had to redo the practical.

Another problem was the location of the equipment. Our request to have our solar panels placed on the laboratory roof was denied. The alternative, to install the panels outside at ground level, was impractical — partly due to the very long cable runs that would have been required and partly because of the high risk of theft.

The long cable runs also meant that even if we could have placed the equipment outside during practicals only, for example to test grid-connection, the resistive losses would have been too great to provide a reliable experimental environment.

We also considered doing a practical on the MPPT. The basic operation of an MPPT unit is to change the loading characteristics on the panel in such a way that the panel is able to deliver the maximum power output possible for the current insolation value.

Various algorithms aim to find this maximum power point, and they all have advantages and disadvantages, from the cost and intricacy of the controller to the complexity of the algorithm itself, the impact on the load equipment, the response times and the sensitivity to temporary fluctuations in the insolation such as a cloud passing in front of the sun.

An experiment on MPPT would be to allow the students to develop their own basic MPPT algorithms, and then to implement that on the MPPT and measure the system to verify its correct operation. However, we were unable to find a commercial MPPT on which we could change the algorithm, especially without having to rewrite the power-electronic control software on a gate driver level. Another thought was to simulate this, and have the students write the algorithms for this environment, but after the first practical we realised that they would get bogged down in the programming and not get to the algorithms, thus not learning what we wanted them to learn.

However, we still wanted the students to make the material their own. As such we opted to divide the class into groups, with each group making a detailed study of a section of the work such as battery systems or grid-tied systems, develop a selection of slides on this, and then present this to the class. The rest of the class took notes and asked questions (as did the lecturers) and the aim was for the students to teach each other.

This was not a perfect substitute, but did yield some very good results. Speaking to students afterwards, and especially again in the design project, it was clear that this was some of the work they internalised the most.

One of the major drawbacks with this was that most of the students found it very difficult to compile a concise set of slides presenting a technical topic. Anticipating this we had students e-mail their slides to us beforehand, and we would provide feedback. For example, there were groups who had prepared 40 slides for a ten minute lecture. So we could give constructive feedback not only on the technical content, but the way it was presented.

In the end this is an effective tool, but one that is only available to small classes. We had the opportunity to do this here, but we would still rather have wanted to do the experiments, showing them how to deal directly with the systems that they will one day be working with.

The Design Project

For the design project we split the class (randomly) into six groups, and gave each group a separate assignment. The assignments are attached in §A.1.4 of Addendum A. Each group was then presented with a system that they had to scope and provide a costing report on.

The design project was challenging, and the results varied greatly. For example, we had demonstrated the software available professionally, such as Autodesk® Ecotect® Analysis[7] that can be used for, amongst other things, insolation calculations. One of the groups obtained a student licence, learned the software and remodelled their entire site and did a complete site analysis. On the other hand, another group did very little, only focussing on the very top layer of the assignment and not addressing any possible problems.

3.4.4 Evolution of the Practicals

For the 2013 and 2014 presentation of the module we tried making changes to see what would work better.

In 2013 we changed the programming language from MATLAB® to Microsoft® Excel®, using the integrated Visual Basic for Application (VBA) programming language to extend the functionality of Excel® in the advanced questions. We did this for two reasons, first that the majority of the work could be completed using only the standard functions of Excel®, and second that it provided more of a visual environment allowing students to enter and retrieve data more easily. It proved marginally better, but it turns out that the students also cannot properly use Excel®.

It should be noted that some of the students, once realising that they did not understand Excel®, endeavoured to improve. One of the design groups, who had only submitted a program covering the basics in practical 1, rewrote their entire program and used VBA to extend the tool to allow the user to perform quite sophisticated analyses, including shadow calculations.

3.5 Chapter Summary

In this chapter we have described the interviews that we conducted. We made observations and discussed our first-hand experiences of the challenges of designing and presenting practicals for a new module. All these aspects provide us with a new set of perspectives on the presentation of practical engineering education in the everyday educational environment.

There are many aspects of the education program that we think require significantly more study, but we have to leave this for future studies. However, we feel that we have helped to provide information on the background of engineering practical education specifically that will allow future researchers to do more focussed studies from the onset. We also provided an example of an approach to the ethical requirements, and how to address them.

[7]From 2015 Autodesk® Ecotect® Analysis is no longer licensed separately, but is part of the Autodesk® Revit® product family.

The work presented here helps us to better understand the current shortcomings of not only the equipment itself, but the system it operates in; or rather the shortcomings of the equipment to support that system. To this end the chapter helps to provide information about the requirements of our educational system. But, what are the limitations or constraints of such a system? In the next chapter we identify some of the crucial constraints and considerations that must be addressed during the eventual design.

Chapter 4

Constraints on Practical Education Systems Development

4.1 Introduction

The aim of this thesis is to determine the requirements of a framework for the development of a new practical engineering education platform. So far we have studied the current systems, as well as the shortcomings of the equipment and the frustrations faced by students, staff and university administrators. This provides us with a good starting point in identifying the various aspects that will need to be addressed by the eventual framework.

However, for the project to have a reasonable chance of success it is important not only to consider the shortcomings that must be addressed but also the environment in which, and for which, it will be developed. This places constraints on the design, but also helps to shape the requirements and give focus to the development.

In this chapter we look at these various constraints and discuss the degree to which they will influence the system. Some constraints, such as the need for the system to be available as a tool for the assessment of student progress, can develop over time and is not required to be fully functional in the first iteration of the system. Other aspects, such as the safety systems, are critical to the operation, and although they can improve over time, are still required from the first unit onwards.

We discuss the constraints under three broad headings: safety, risk management and legal requirements; development sustainability; and teaching and learning.

4.2 Safety, Risk Management and Legal Requirements

Engineering is an inherently dangerous activity, because of the forces that are harnessed by various machines and equipment to perform work. But, crucially, this is not done irresponsibly or without detailed consideration of the risks. The management of risk is critical for the safe operation of dangerous systems.

Practicals in engineering education have to allow students the opportunity to experiment with these same forces; both to teach the principles of their operation as well as how to use them safely. As such the practicals share the danger of the professional engineering environment.

But the aim of risk management is to *manage and mitigate the risks, not to remove them*. Every action has some element of risk attached, and the only way to realistically remove all risk is to do nothing. However, through careful examination of a system it is possible to mitigate risks or where one cannot, set up procedures for the management of those risks.

In South Africa safety in the workplace is covered by the Occupational Health and Safety Act (OHSA). The purpose of the act is: "To provide for the health and safety of persons at work and for the health and safety of persons in connection with the use of plant and machinery; the protection of persons other than persons at work against hazards to health and safety arising out of or in connection with the activities of persons at work[. . .]"[South Africa: Department of Labour, 1993] There are similar legislation and governing bodies in most countries, such as the European Agency for Safety and Health at Work (EU-OSHA), an agency of the European Union.

The OHSA aims to ensure the safety of both people working with dangerous equipment, as well as those who can be endangered by it even if they are not using it themselves. This is especially problematic for a university laboratory where there are many people and lots of moving or live equipment. The laboratory must be made safe, but not dull the learning experience. And simply providing more personal protective equipment is not the solution. The act promotes the escalation of safety standards as required, rather than simply applying a worse case scenario to every instance of risk.

A very good example of the balance of escalation is that, as part of their duties, the employer must be shown to be "taking such steps as may be reasonably practicable to eliminate or mitigate any hazard or potential hazard to the safety or health of employees, before resorting to Personal Protective Equipment (PPE)."This is the difference between placing an electrical machine in a noise-reduction enclosure, rather than requiring students to wear ear-plugs. However, the use of "reasonably practicable" in the act is problematic as it does not specify an objective standard, but rather requires the reasonable effort by the employer; in our case the laboratory management and the university. So, in the example above it is reasonable to ask whether the excessive cost of a noise cover is *reasonably practicable*, and if this permits you rather to use cheaper PPE?

Although the act pays careful attention to the prevention of serious injury and death, it also addresses the issue of repetitive strain injuries, both musculoskeletal damage as well as hearing loss, etc. The Noise-Induced Hearing Loss Regulations, an amendment to the OHSA, set out clear guidelines for the limitations on continued noise as well as peak noise, and the ways in which this must be monitored.[South Africa: Department of Labour, 2003] But to address these safety requirements is not simple, since the monitoring and measurement of noise has to be carried out according to strict International Organization for Standardization (ISO) standards (or their local equivalents) which for noise includes a list of more than 20 standards, most notably ISO 3740:2000, ISO 1996-2:2007 and ISO 532:1975. Given the complexity, the laboratory will either have to train somebody and buy the equipment, or it will need to contract a firm to do the assessment for them. [International Organization for Standardization, 1975, International Organization for Standardization, 2000, International Organization for Standardization, 2007]

But not every risk is so clearly measurable. Ergonomics, for example, is very difficult to measure objectively, and addressing any found problems can be very difficult and expensive. Furthermore, it is possible that the mitigation of one risk results in the worsening of another. The identification, management and mitigation of risk is something that each university will have to complete for itself.

What are the limitations on newly designed equipment? Given that the system will be developed by multiple groups, what are the legal responsibilities of each, and what is the legal exposure in the event of an accident? Under the GNU General Public License (GPL), the licence used by many open source software programs (including Linux), states the limitation of the developers' liability, declaring that "In no event unless required by applicable law or agreed to in writing will any copyright holder, or any other party who modifies and/or conveys the program as permitted above, be liable to you for damages, including any general, special, incidental or consequential damages arising out of the use or inability to use the program (including but not limited to loss of data or data being rendered inaccurate or losses sustained by you or third parties or a failure of the program to operate with any other programs), even if such holder or other party has been advised of the possibility of such damages. [Original written in all capitals.] "[Free Software Foundation, 2007]

But, can this agreement extend to hardware, where the system has a physical effect, which can potentially injure or kill a user? What is the level of reasonable care required for a design? The surety of a safe system is a benefit of a professionally developed product, and although their adherence to ISO (and equivalent) certifications is not a guarantee of safety, it is at the very least a good minimum standard.

4.3 Development Sustainability

A university is a research institution, not a product development company, and as such is not set up to develop new commercially ready systems, nor is it necessarily interested in doing so. To develop a sustainable system for practical engineering education, it needs to grow beyond the interests of a single research project, and must not only address issues of practical education but must do so in a way that researchers (both postgraduate students and staff) are able to advance their careers and reap additional benefits from the development of the equipment.

There is, as we observed in Chapter 3, already a great deal of pressure on the time of postgraduate students because of teaching assistant duties, leaving little time for even more additional work. However, if the development of the equipment can coincide with their research, they will not only build a system to support the students, but one that can help them (and their laboratory) to advance faster. The developed equipment must therefore be able to be used both in the practical laboratories, and in research projects.

This type of development would help to contribute to the university's knowledge base. Even though the university would share the developed work with other universities, it would have benefited from the work done by other universities, and its staff will remain experts in their aspect of the developed system. The challenge from a systems development perspective is to ensure that the benefits for a university in using the shared architecture is significantly better for them than to develop a system on their own.

Shared development has another challenger in the form of the intellectual property protection enforced by many universities. In South Africa universities are, mostly, state funded. The *Policy in Respect of Exploitation of Intellectual Property* of Stellenbosch University notes that: "[...] all rights, interest and title in any invention, plant breeder's right, design, trade secret or knowledge, whether registerable or not, created by such staff members of SU[Stellenbosch University] in the normal scope and course of their duties and obligations to SU, vest in SU, and in so far as these do not vest by law, staff members assign and shall assign such rights and interests to SU. Unless otherwise agreed, this shall include all inventions and knowledge developed by the staff members in the field of specialisation in which the said staff members have been appointed at SU." [Stellenbosch University, 2009] This is in keeping with the directives of the South African Government, outlined in the *Government Gazette Notice on the Interpretation of the scope of The Intellectual Property Rights from Publicly Financed Research and Development Act (Act 51 of 2008).*[South Africa: Department of Science and Technology, 2012]

Although the aforementioned limitations are problematic, Stellenbosch University has already inserted clauses specifically for staff and students who wish to develop open source software. It seems reasonable that this could be expanded to include hardware systems. But, it will take time as the policies of the universities would have to be changed.

Having discussed the one aspect of staff and postgraduates working on the system, the other equally crucial aspect to focus on is the cost of the development and deployment. As discussed in Chapter 2 the cost of researching and developing such a system is something that needs to be considered carefully. The modularity and flexibility of the system provides a way to address this. In return for spending time developing a component of the practical education system the researcher benefits because they are able to develop a more powerful component than they would otherwise have been able to, thanks to the already available components and designs.

Only one possible solution is suggested here and that must be examined closely when the development framework is being designed, lest the system's progress be mired not by the challenge of the technical design but by a funding limitation.

Several other factors, which we refer to as university environmental factors, must also be considered for the project to be generally acceptable. In §3.2.2 we discussed the conversations with the technical staff who are responsible for the operation and maintenance of the laboratories. It cannot reasonably be expected that they must be completely versed in the design and development of the system simply to operate and maintain it. The final system will have to be developed in such a way that the staff are able to maintain and service it, which would require detailed user and service manuals.

This also applies to the integration of the system into the information technology infrastructure of a university. The systems which integrate with the network will have to be very well documented, and should allow for various network integration strategies. The reason for this is twofold: the network must be protected from malfunctions of the practical equipment and the equipment must be protected from the network, specifically from malicious behaviour.

Another key university environmental factor is the way in which staff are evaluated and promoted. If staff members spend time developing components for such a system, they will invariably want to demonstrate progress. To support the lecturer, it is important that the framework aims to set development cycles of no longer than a year, and that it provides guidelines for the evaluation of progress.

There are other factors that could be included here, but, they differ among universities, faculties, departments and even research groups. Providing institutions with a way to benefit from the practical engineering education system regardless of their combination of factors is paramount to the success of the project.

4.4 Teaching and Learning

We have discussed, in detail, the impact of the system on practical education — specifically on improving and facilitating experimentation. But direct experimentation is not the only teaching environment in engineering. Our final set of design considerations comes from investigating other areas of pre-graduate engineering education where such a system could be applied. We will look at two such areas, namely the use of the system as a teaching tool during lectures, and as a student evaluation tool.

During the interviews (§3.2) we discussed the response of a lecturer who pointed out the frustration of wanting to be able to introduce elements of the practical, or simply of a physical system, during lectures. This was impractical because of the system's size, power, and equipment requirements. As we will discuss in a later chapter, the measurement and instrument display of the proposed system do not have to be physically connected, but can be data-only interface; effectively a *fly-by-wire* interface. Thus, it is irrelevant if the screen displaying the interface is on the bench next to the equipment or running on the lecturer's computer in the classroom.

This separation also means that all the practical setups will be able to function as remote laboratories, something we will discuss in more detail in a later chapter. The framework, however, must allow for the expansion of the system into this avenue.

Another advantage of the *fly-by-wire* approach is that every parameter, input and output, can be measured and recorded. This allows for the possibility to make a recording of a practical session that can be reviewed later. The lecturer can review whether the student has completed a practical, look at any problems experienced by the student or simply look at the speed with which each section of a practical was completed, which might help identify students who are struggling with specific sections of the work.

This would also allow examinations to be completed in the laboratory, since students could be provided with a random system that they must characterise or experiment on during an examination setting, and the equipment would be able to record the session and to support the lecturer in evaluating the work by checking provided results against expected answers.

For these types of systems to work, it will have to provide security and to identity verification and several other features that allow the university to verify the validity of the student's examination submission. But delete such features could also allow students to use the laboratory remotely, 24 hours a day, performing complex and additional experiments in their own time.

4.5 Conclusion

In this chapter we have identified various constraints that will have to be addressed by the development framework. But several of the constraints, specifically those applicable to the legal responsibility of the developer, risk assessment of the equipment and laboratory still requires more study. The ownership of intellectual property is also a challenging aspect, as it will require research into a set of legal guidelines that would be universally applicable — which is beyond the scope of this study.

Chapter 5

Preliminary Prototypes

5.1 Introduction

So far we have made a detailed study of the engineering education environment with specific focus on the presentation of practicals. In the following chapters we investigate the design of the equipment itself. Our aim is to understand the challenges surrounding the design of new equipment for the purposes of practical engineering education, so that we may make recommendations on a proposed development strategy that will be able to deliver results and be sustainable.

We do this through the design of a series of three prototypes. In this chapter we detail the design and development of the first two prototypes, as well as introduce the third and final prototype at the end of the chapter. The detail of the third prototype is then provided in the three subsequent chapters. Our aim, however, is not to develop a working and bench ready system in this thesis, but to focus on testing various approaches and methodologies.

We also want to look at the elements of design that are not typically addressed in engineering research projects, namely the aesthetics, usability, cost-effectiveness, constructibility and maintainability of the design and the factors that enhance or adversely affect these aspects.

Due to the complexity of the equipment, the variety of use-cases, and the strict focus on human interaction and usability, our aim was to start prototyping early and to prototype as much as possible. This methodology is supported by designers such as Bill Moggridge who advocates this type of design, noting that by making each iterative step more realistic, you allow room to get feedback, spot problems, and generally allow space for growth of the idea.[Moggridge, 2007]

5.1.1 Usability through Design

Many aspects must be taken into account when developing a good product that meets more than just the technical specifications. Design of equipment cannot simply refer to the electronic design, and product developers have to familiarise themselves with these other design principles. So, although we will discuss a good many techniques during the course of the following chapters, it cannot serve as a replacement for a detailed study of design theory.

We want to ensure that we focus as much as possible on the usability, of all our designs, allowing users to operate the equipment simply. This not only minimises safety risks, but also increases the amount of time users spend experimenting, rather than learning the equipment itself. We decided on a number of design principles, as described by Lidwell, et al, to help with the design process.[Lidwell et al., 2003]

It is important to note that some of these design principles are known by several different names, depending on the profession describing it. One such example is the *Pareto Principle*, which a quick literature search shows is also known as the *principle of factor sparsity*, *Juran's Principle*, the *80/20 Rule*, the *law of the vital few and the trivial many*, and so forth. For the sake of clarity and conformity we will use the names as given by Lidwell, et al.

5.2 First Prototype

5.2.1 Overview

For the first prototype we started with the idea of developing a set of equipment for practical education that mimics the look of an electronic circuit, but on a symbolic level rather than a physical one.

We used the solar energy practicals of ES414 as an example, allowing us to determine a broad set of requirements that we can use as a test case. We designed a circuit (show in Figure 5.1) that could be used during these practicals to perform various experiments on solar panels.

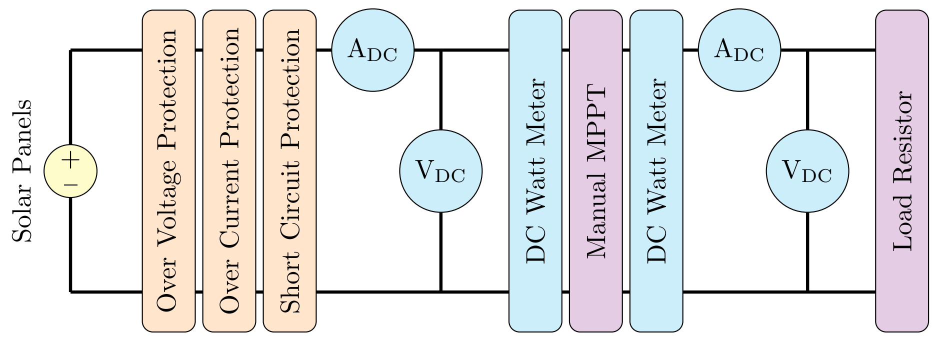


Figure 5.1: System diagram of the first prototype.

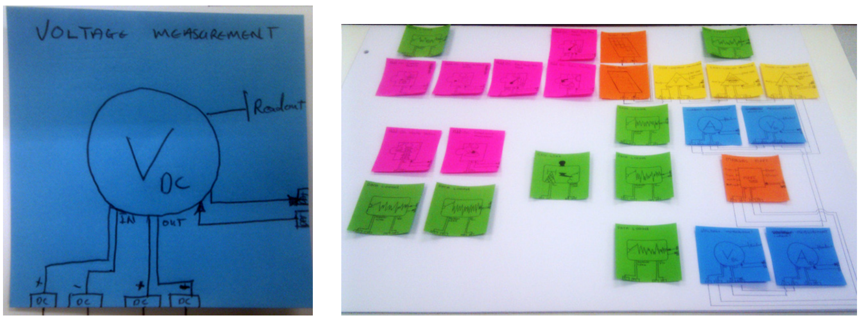
The use of *mimicry* in design supports usability by providing the user with a known interface. Even though it is a brand new system, by injecting elements of the familiar one helps the users to set up the appropriate mental models for working with the new system in terms of what they know. It is important to note that the process of mimicry is how people learn new systems, namely that they try to understand new things by relating them to things they already know.

This is encapsulated in the *mental model* design principles, and requires that the designer pay detailed attention to the experiences that people have when using a new system for the first time. Since people will default to what they know, they will attempt to operate new equipment according to the expectations of a model they already have. If such behaviour by the user will be detrimental to the system, it is imperative that the designer pays close attention to it and introduces elements to waylay any such errors.

One way to identify and mitigate such errors is through regular prototyping. We started our prototyping process on paper, by physically sketching out the various *modules* that would be needed.

As for the system itself, our goal was to design an equipment set that would allow the students to build, safely and rapidly, and on a symbolic level, the circuits they would need for each experiment. This meant that the equipment on the bench must be clearly indicated, be simple to connect, require only a rudimentary wiring diagram, and not be cluttered with wires.

To identify the type and complexity of equipment we would need we started by sketching, on little pieces of coloured paper, each of the modules that we thought could be required. Each module was drawn as a black-box system, denoting the function as well as the input and output connections and information. An example of such a module is the direct-current voltage meter, which can be seen in Figure 5.2a. Each colour denoted a different kind of module. Blue, for example, was used for metering equipment and yellow for protection equipment. The next step was to combine the various modules by laying them out on a large sheet of paper and drawing in the interconnections, as can be seen in Figure 5.2b.



(a) Example of one of the first paper prototypes, simply done on coloured paper stock.

(b) The paper version, detailing the interconnections.

Figure 5.2: Some of the paper prototypes used in the development of the first prototype.

Although crude, this basic style of prototyping allowed us to develop new ideas rapidly. We were able to sketch modules, make changes, discuss various options and redraw any element in order to capture all the feedback and suggestions. We were still conducting observations and interviews at this time, and this specific prototyping method allowed us to consider all these responses and observations.

Through this process we decided on a system consisting of various modules including direct-current meters, protection modules, a manual duty-cycle step-down converter and various connection point modules, all connected together on an interconnection board. The next step was to start looking at the detailed physical and electrical design of the various modules as well as the interconnection board.

The **physical design** is one of the most limiting factors since the size and shape of the equipment place fixed limits on the amount of electrical energy that can be transmitted and dissipated in the various modules as well as in the interconnection board. Although the electronic system can be designed first, we wanted to ensure that the system was not only functional but also aesthetically pleasing. The aesthetics of a design is not simply a matter of vanity, but rather a crucial aspect in the usability of a design, due to the *aesthetic-usability effect.* This effect states that the apparent usability of a design is strongly affected by its aesthetic aspects rather than the inherent usability.[Kurosu and Kashimura, 1995]

We also wanted users to be able to easily handle each module, and to ensure that the modules were rugged as well as electrically isolated during operation. We started investigating various handheld enclosures, and settled on the *Series 33 Grip-Cases* from CamdenBoss. The cases are 185 mm by 110 mm and 35 mm deep. These units are available off the shelf, making them simple to adapt and replace in the event of damage or if the laboratory needs to be expanded. The units also have a series of interchangeable coloured corner grip-points, which would allow us to easily colour code the different pieces of equipment. A rendering of the units, with the different coloured bands, is shown in Figure 5.3.

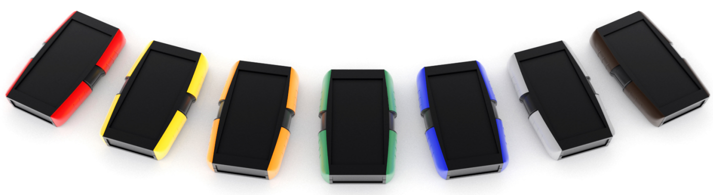


Figure 5.3: Rendering of the range of Series 33 Grip-Cases by CamdenBoss, showing the various interchangeable coloured corners. *(Rendering by Author)*

With the enclosure selected we were able to continue with the design of the various modules. In the following sections we proceed to develop the various elements and modules of the system.

5.2.2 Equipment Interface

Because each module is a stand-alone unit, all its control and feedback mechanisms must be contained within the unit itself. But the modules do function together as a whole, and when the students are using the system they will be looking at several modules at the same time.

From observations and interviews we learned that students struggle with the current metering equipment for three main reasons, namely that the meters all look similar and thus it is difficult to tell them apart; that the scale indicators and metering displays are not always clear, which make quick reading of measurements difficult; and finally that the measurement range indicator is obscured, which causes them to overload the equipment.

Using the DC Voltmeter module as an example case, we started to design a user interface that would address these problems. The result is shown in Figure 5.4.

Legibility is improved by using black text on a light-grey background. A white background would be problematic if used outside in direct sunlight. The type of meter is clearly indicated in the name at the top but also, crucially, as circuit diagram on the bottom of the meter. The diagrammatic representation shows not only what type of meter this is, but also how it connects into the system — which we will discuss in more detail in §5.2.4 through §5.2.9. The module class is also indicated by the colour of the corner points on the enclosure itself, which further aids quick identification of the module — in this case red to denote metering modules. An artist's impression of the complete DC Voltmeter can be seen in Figure 5.5.

The unit also provides several readouts and indicators. The metering information is displayed at the top of the unit using a transflective Liquid Crystal Display (LCD) with a Light Emitting Diode (LED) back light, ensuring that the unit will be legible both in direct sunlight and in a dark laboratory. The specific colour of the LCD (white active pixels on a blue background) was chosen to further enhance the design aesthetic.

Below the readout screen there is a series of buttons, as well as an indicator light above each one, to select and indicate the current measurement scale. The scale determines the highest permissible value measured by the unit. We will discuss the implementation of the scale system in §5.2.5. For now it is important to know that exceeding the scale will not damage the meter, but rather trigger a soft-fail.

Surrounding the display and control section is a ring of LEDs. This ring-

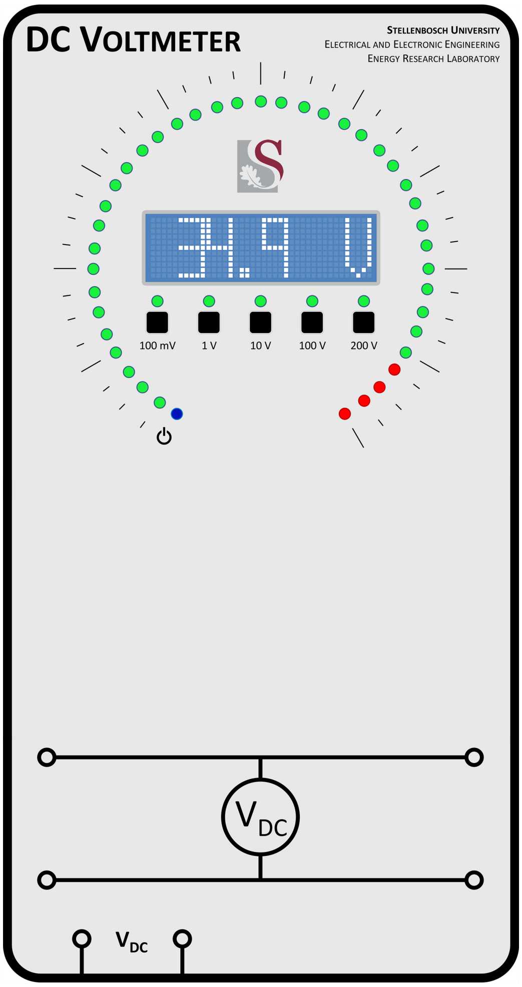


Figure 5.4: The front-plate of the DC voltmeter from the first prototype, demonstrating the layout of the user interface.

display is a quick status indicator for the meter. The ring is read clockwise, starting with a blue LED to indicate that the meter's power supply is functioning and that it is ready to measure, and proceeds to fill up as the measured voltage increases, terminating in four red LEDs when the measured voltage exceeds 90% of the currently selected range.

Because of the gradual and visible increase on the circular indicator it allows users to see potential over-voltage situations sooner, allowing them to compensate for this faster. Although the accessibility of the circular indicator is slightly diminished for some colour blind users (due to the requirement to make distinctions between red and green), the fact that the scale clearly lights up from one end to the other is still a strong enough indicator.

When choosing the use of colour on the user interface it is important to avoid interference effects that may adversely affect the user during operation. An interference effect is a phenomenon by which the accuracy and speed with which a task

Figure 5.5: The DC voltmeter from the first prototype. *(Rendering by Author)*

is performed is adversely affected by the presence of secondary interference that causes a competing mental process.[Lidwell et al., 2003] The best known example of this is the Stroop Test. Stroop and his team presented subjects with a pair of conflicting stimuli; namely a list of colours with each one on the list printed in a different colour than the word itself. (So, for example, the word 'red'would be printed in blue.) They noticed that the time required to read out the words increased when the subjects were required to read the words with the conflicting stimuli.[Stroop, 1935]

Similarly in this design we have to ensure that the indicators and colours being used, as well as any dynamics (such as flashing one of the indicators) is in keeping with the expected result of that indication. For example, using only red LEDs on the circular indicator will give the impression that the system is always in danger, potentially lessening the response to an actual over-voltage event.

5.2.3 Electrical Specification

The next stage of the design is to determine the electrical specification of the experimental setup as a whole, as well as the allowances and requirements of specific modules. The system is split into two environments, namely the experiment side, which is where energy flows from the solar panels through to the load resistors, and the back-end which supplies the various modules with operating power as well as the data lines that allow them to interconnect.

The Experiment Side

The maximum power levels on the experiment side depend on the solar panels that will be experimented on, as well as the number of these panels and the specific configuration. We decided to allow up to two panels at the same time, connected either in series or in parallel depending on the specific experiment being conducted. Furthermore, we based our calculations on the Suntech STP-290-24/Vd panels. We chose these specific panels because they represent a high-end panel, and were similar to the panels that we were using in the ES414 practicals at the time. With a rating of 290 W at standard testing conditions these panels also represented some of the highest powered units available, providing a good indication of the maximum required power capability of the system.

Another important factor to consider is the nameplate values of the solar panel versus the actual response in the field. The panels' nameplate values are determined during manufacturing and are conducted at Standard Testing Conditions, which is 1000 W/m^2. However, in South Africa we get as much as 1250 W/m^2, which could result in substantially higher power outputs than the nameplate value. Assuming the worst case scenario, this could result in an increase of up to a quarter more than the nameplate value. This increase does not have a significant effect on the open-circuit voltage, since the open-circuit voltage is an attribute of the solar cell construction rather than the incoming solar energy. But the current is in a direct linear relationship with insolation, resulting in increased short circuit current given increased insolation.

In terms of the electrical capacity we have to consider the maximum voltage, current and power levels. The **maximum voltage** will be reached during open-circuit conditions, with two panels in series, giving two times the single panel open-circuit voltage of 44.9 V_{DC}, which is 89.8 V_{DC}. As mentioned, this value is relatively insensitive to increases in solar insolation, and thus does not need to be adjusted.

The **maximum current** will be reached during short circuit conditions, with two panels in parallel. The individual panel short circuit current is 8.53 A_{DC}, but since we assume a worst case scenario of an insolation of 1250 W/m^2 we increase the rated value by 1.25, giving us 10.7 A_{DC} per panel. With two panels in parallel we get a maximum current rating of 21.4 A_{DC}.

Finally the **maximum power** is the sum of the individual power values, compensated for increased solar insolation. The panel's unadjusted maximum power point value is 290 W_{DC}, which becomes 362.5 W_{DC} when compensating for increased insolation, resulting in a combined maximum system capacity requirement of 725 W_{DC}.

The Back-end

To ensure that the modules do not affect the experiment being conducted, we decided to provide each unit with a separate power supply. This also isolates the modules from the circuit being measured. The system, through the interconnection board, provides each module with its own power supply of 12 V_{DC}. Since the system must be usable outside, we want it to be able to run off of a large capacity lead-acid battery for the entire duration of the practical. Assuming a worst case scenario this will be a full afternoon sessions lasting five hours. A large, but still physically manageable, 12 V lead-acid battery is capable of providing 24 Ah of energy. If we shallow cycle, we cannot empty more than 50% of the battery's charge without damaging the unit. This provides 12 Ah, limiting the maximum delivered current to 2.4 A_{DC}, spread over 12 units, resulting in an absolute maximum of 0.2 A_{DC} at 12 V_{DC} per unit, or 2.4 W_{DC}.

This is a major restriction, as there are 41 LEDs on the circular indicator alone. As an example, if we used Vishay TLHG5400 green 5 mm LEDs the LED indicator circuit alone would need 1.968 W_{DC} (0.048 W_{DC} per LED), leaving only 0.432 W_{DC} for the remainder of the module.[Vishay Semiconductors, 2015]

The alternative is to specify that two batteries must be used, but this dramatically increases the cost of the batteries, and it also complicates the work of the laboratory staff as they have to charge and maintain all the battery systems. It also makes the system very heavy and cumbersome to set up.

5.2.4 The Interconnection Board

The interconnection board serves to provide a safe and clutter free way to connect the various modules together, allowing the energy from the experiment circuit to be conducted through all the modules as well as providing each module access to the power supply and data buses. The board also provides a rigid surface that serves as a workbench for the practical, and can easily be carried outside and placed near the rest of the experimental setup.

The interconnection board has an internal wire routing that connects to the modules via a set of male connection pins located on the rear of each module, shown in Figure 5.6a that mate with a set of female receptacles on the interconnection board, shown in Figure 5.6b. There are ten pins in total, the outer five pins for the experiment side and the inner five pins for the back-end. The bottom pin, which is the earthing pin, is slightly longer and is used as an orientation key to help align the unit when plugging in, ensuring that the unit can only be connected one way. The longer pin also ensures that the ground is the first circuit to be connected and the last circuit to be broken during extraction.

The pins for use on the experiment circuit are 6 mm in diameter and the data and power buses 3 mm each. The 6 mm diameter copper conductor has a current capacity in the order of 170 A. This provides a current capacity of between 80 A and 100 A for the 6 mm pegs and 33 A to 46 A for the 3 mm ones, using the current capacities for copper in an enclosed environment.[Van Valkenburg and Middleton, 2002] This is a safety factor of more than 3.73 on the maximum values defined for

(a) The connection pins located on the rear of each unit.

(b) The receptacles located on the connection board.

Figure 5.6: The male and female connection terminals of the first prototype. *(Rendering by Author)*

the experimental circuit, and more than 60 times the maximum value specified for the power supply bus.

Each module has four pins that connect it to the experiment circuit. Two pins are for the incoming power and two for the outgoing. The wiring in the interconnection board is such that the top and bottom pins of the outgoing power side of one module are connected to the corresponding top and bottom pins of the incoming power side of the next module, as can be seen in Figure 5.7. Wiring inside each module determines how the modules are linked to the board and thus to the other modules.

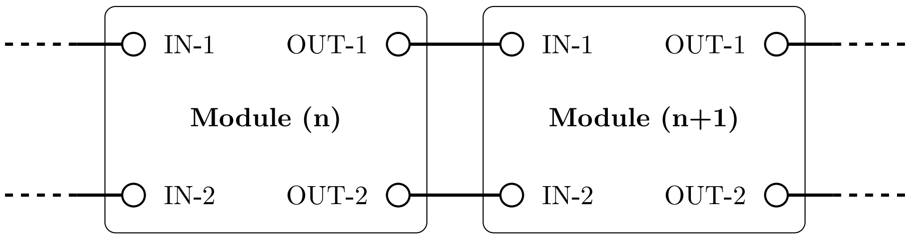


Figure 5.7: Example of the module interconnection from the first prototype.

For clarity the routing is printed on the front plate of the interconnection board, the design of which is shown in Figure 5.8. In total there are 12 identical connection terminals, except one slot that has a larger footprint although the electrical connection is still the same size. Even though the connections are identical, the printed front-plate shows the areas of the board grouped and colour coded to help identify the module type that should be used during every stage of the circuit. The wiring shown on the front-plate also matches the circuit diagrams shown on the various modules, helping users to understand the interconnection.

The board itself is 40 mm thick, and consists of a rigid steel structure, providing support for the panel against buckling. The board is suspended between two wooden side-walls which serve to lift the board off the ground, as well as to tilt it 10° forwards, allowing easier access and a better working position for the student.

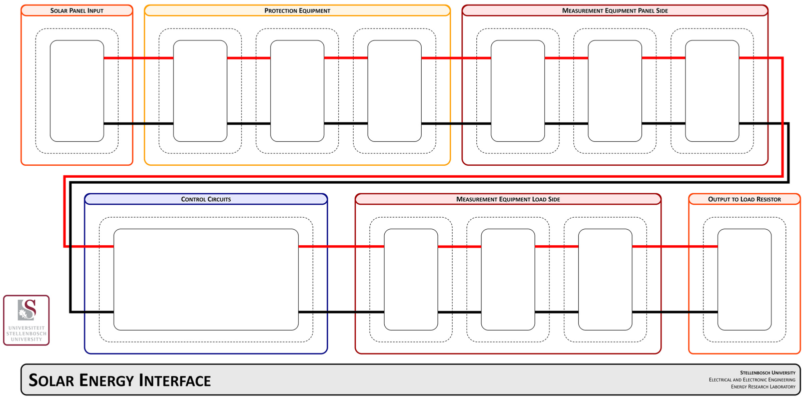


Figure 5.8: Printed front-plate of the interconnection board from the first prototype.

The front panel of the board is an acrylic plastic, which together with the wooden side-frames and the Acrylonitrile Butadiene Styrene (ABS) plastic grip-cases of the modules themselves, ensure that there are no conductive surfaces that the user can touch.

An artist's impression of the interconnection board is shown in Figure 5.9. In this rendering the board is fully loaded with modules, and has wires leading away from it that will connect to the solar panels and the dummy-load resistor, although they are not shown.

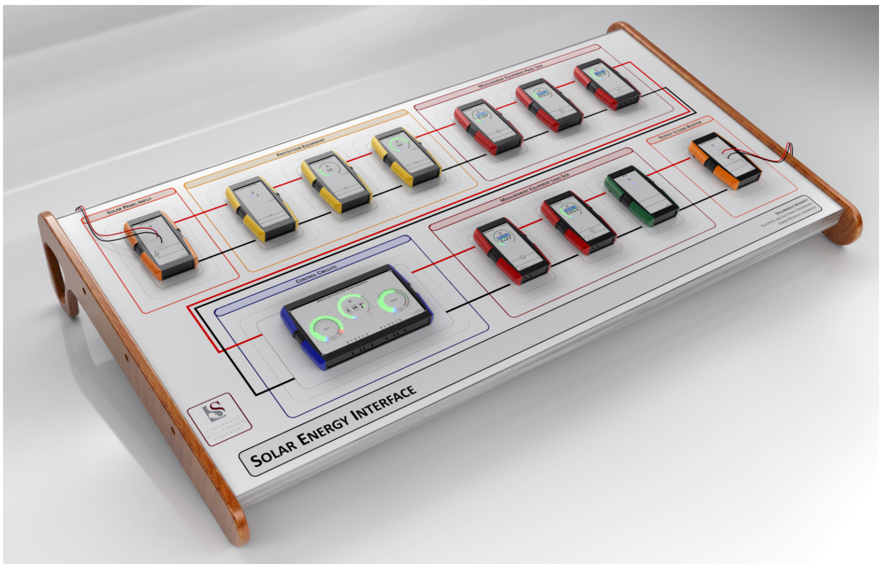


Figure 5.9: The interconnection board of the first prototype, fully loaded with various modules. *(Rendering by Author)*

5.2.5 Metering Modules

As mentioned earlier, we are using the solar energy practicals of ES414 as an example and have derived our system specifications from these. According to these specifications we require three metering modules, a DC Voltmeter, a DC Ammeter and a DC Wattmeter.

The metering equipment allows the user to measure the specific parameter of the circuit wherever the meter is inserted. Since the connection circuitry of the module is connected internally it is impossible to incorrectly connect a meter to the circuit. This avoids students accidentally connecting a voltmeter in series or an ammeter in parallel to the circuit.

Each meter also provides a set of connection terminals that protrude from its side plate. These provide a reference point for the connection of external measurement equipment, such as oscilloscopes. On voltmeters the terminals provide a direct connection to the voltage being measured, but on ammeters the terminals have a small shunt-resistor that converts the current into a voltage that the user can measure.

The meters have a similar interface, which has already been discussed earlier in §5.2.2. The key factors are to select the values for the scales as well as to determine the required measurement accuracy of each module.

The selection of measurement accuracy is a key aspect where we deviate from the design decisions of commercial equipment. Through our interviews and observations we came to realise that university students do not necessarily need highly accurate measurement equipment, but rather require robust units that are inexpensive enough so that more units can be purchased.

Furthermore the use of multiple scales complicates the construction as well as maintainability of the equipment. Our solution is to select a full scale value, and then to measure all the currents and voltages using that single full scale. Accordingly the scale selectors on the modules are only a software processed result, meaning that an over-voltage or over-current mistake on a scale that is not the full scale value will only result in a soft error, without any risk of damaging the unit.

Metering Module: The DC Voltmeter

The DC voltmeter (shown in Figure 5.10) has five full scale settings, each a factor ten higher than the last, with a full scale setting at the end. The resulting scale settings are 100 mV, 1 V, 10 V, 100 V and 200 V. The meter has no internal protection, and will be damaged if voltages exceed the safety limit, which is 10% above the full scale value, or 220 V_{DC}.

The next step is to determine the meter accuracy. The full scale value, includ-

Figure 5.10: The DC voltmeter metering module of the first prototype. *(Rendering by Author)*

ing the safety factor, is 220 V_{DC}. We will be using an analogue to digital converter to measure the voltage. Considering that the input signal will contain some noise, we choose to ignore the two least significant bits from the conversion. So, when selecting an Analogue to Digital Converter (ADC) we need to take this reduction in resolution into account. Table 5.1 details the resulting voltage resolution given various ADC conversion resolutions.

Table 5.1: Voltage measurement increments for various ADC resolutions.

ADC Resolution (Bits)	ADC Adapted Resolution (Bits)	Measurement Increment (mV)
8	6	3437.500
10	8	859.375
12	10	214.844
16	14	13.428
20	18	0.839
24	22	0.052

The system will rarely require students to measure below 1 mV, which allows us to use the 20-bit ADC. Another cost saving feature is that the system does not need to measure too quickly, since the parameters of a solar system will change relatively slowly. A measurement frequency of 1 Hz will be sufficient.

Metering Module: The DC Ammeter

The DC Ammeter (pictured in Figure 5.11) has only four full scale settings, increasing in factors of 10 with a deviation only for the maximum scale. The scale values are 100 mA, 1 A, 10 A and 30 A.

Since this is a DC current measurement, the simplest and most robust solution is to use a shunt-resistor. The aim is to limit the power lost inside the meter-resistor as much as possible, while maintaining a good measurement current. Using

Figure 5.11: The DC ammeter metering module of the first prototype. *(Rendering by Author)*

a 100 mΩ resistor the power loss in the resistor at the maximum current point is 1.5% of the total power, or 10.89 W_{DC} on 725 W_{DC} . At 100 mA_{DC} this would constitute a power loss of 100 μW_{DC} which is less than the measurement modules are able to measure.

Given that the full scale value (including the safety factor) of the ammeter is 33 A_{DC}, then a 16-bit ADC with the two least significant bits removed will yield a measurement increment of 2.014 mV_{DC}.

Metering Module: The DC Wattmeter

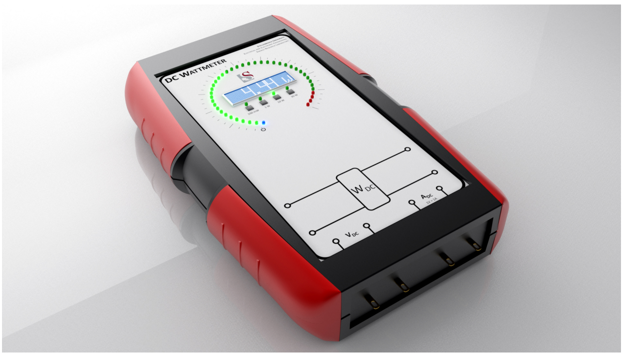


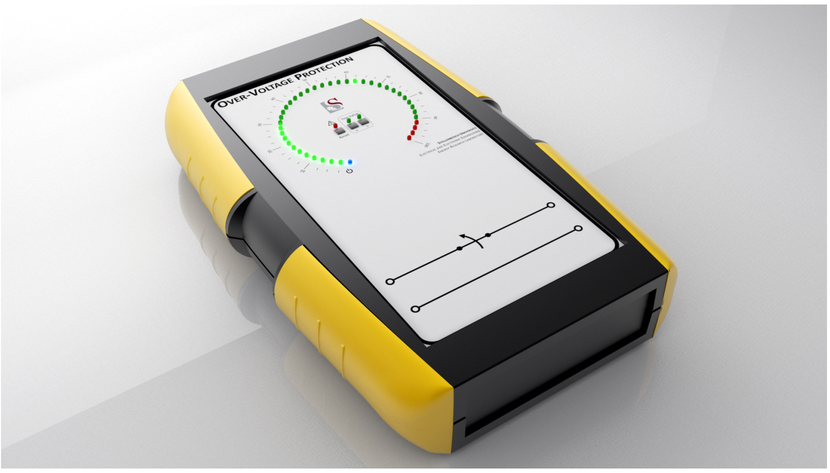
Figure 5.12: The DC wattmeter metering module of the first prototype. *(Rendering by Author)*

Finally we also develop a separate DC Wattmeter (pictured in Figure 5.12). Although it is fairly simple to calculate the wattage if the current and voltage is known, the aim of the system is legibility and quick referencing. Furthermore, one of the key aspects of a solar energy system is the ability to find the maximum power point, and we want to ensure that students are able to observe the increase in power as the voltage and current point of the solar panel is changed during practicals. To this end, we also propose a dedicated DC wattmeter.

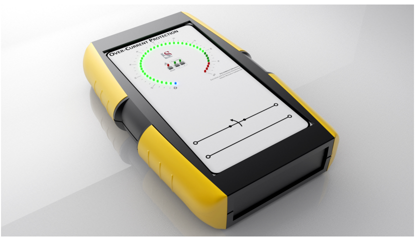
Internally the wattmeter uses the measurement systems, including firmware, of the voltmeter and ammeter. This is the first demonstration of the use of a modular design approach. Our aim was to ensure that the various components of the system could be used interchangeably. This both speeds up the development of new modules, as well as promotes the simplification of servicing, since the shared components can be removed and replaced as a single part.

5.2.6 Protection Modules

The protection modules allow the user to set up custom protection levels for over-voltage and over-current conditions. For our purposes we designed three modules, namely a DC over-voltage protection module (shown in Figure 5.13a), a DC over-current protection module (shown in Figure 5.13b) and a DC short-circuit protection module (shown in Figure 5.13c).



(a) Over-voltage protection module



(b) Over-current protection module

(c) Short-circuit protection module

Figure 5.13: The various protection modules of the first prototype. *(Rendering by Author)*

The protection modules monitor the circuit, and will isolate it if the designated values are exceeded. Although to some degree this protection is provided for the safeguarding of various other modules, the purpose is mainly instructional. As discussed in the previous section, the measurement modules have very high maximum tolerance values, and will only need protection in the event of serious errors. In the general context the protection modules allow the students to become accustomed to the practice of protecting electrical circuits.

However, in larger practical set-ups, such as motor drive practicals, the protection modules will serve a more substantial purpose as not all the equipment will be able to handle the over-current and over-voltage conditions.

Although the short circuit protection module is similar to the over-current protection module, this unit is able to detect short circuit conditions before an over-current error occurs. However, there are certain experiments, such as the short circuit load test, where this unit will negatively interfere with the test, and students will have to know when to disengage protection circuits — as this is the same principle that has to be followed during other experiments in the laboratory.

The user-interface of the protection circuit is simpler than those of the measurement modules. There are no scales. The circular indicator reaches its maximum at the peak voltage or current level that it can sustain. Using an increment and decrement button, the user selects the desired protection level in 2.5% increments. A blinking LED on the circular indicator shows the currently selected protection level. As the voltage or current increases, the LEDs will light up to show the current level, and when they reach the level indicated by the blinking LED the protection module will engage and isolate the circuit. To indicate that the protection is engaged the error LED (in red) will start flashing, along with all the lights on the circular indicator indicating the level. The user can then reset the unit with the *Reset* button.

5.2.7 Connection Modules

We need two types of connection modules. The first one is called a Bridge Connector Module and is indicated using green case markers. These modules bridge the experiment side of the circuit over unused module slots on the interconnection board. The second type are External Connection Modules and are indicated using orange case markers. These units are used to connect external equipment to the board.

The Bridge Connector Module

The experiment side circuit connections on the interconnection board break at every slot, allowing a module to be connected. However, if an experiment does not require the use of all the module slots, then a Bridge Connector Module can be inserted to bridge the slot.

The Bridge Connector Module (shown in Figure 5.14) is a simple unit that directly connects, through internal wiring, the input and output circuits. It also has a single LED that is wired through a currently limiting resistor directly to the

Figure 5.14: A bridge connector module from the first prototype. *(Rendering by Author)*

power bus, which will indicate if the unit has been properly plugged into the slot.

The External Connection Modules

The External Connection Modules are used to connect external hardware components to the interconnection board. In the example system we are developing this includes a Solar Panel Connection Module, shown in Figure 5.15a, a Load Resistor Connection Module, shown in Figure 5.15b, solar panels and the load resistor.

(a) An input module. (b) An output module.

Figure 5.15: The external interface modules from the first prototype. *(Rendering by Author)*

On both modules the jumper leads are part of the module itself and are connected to the external equipment on site. This allowed us to use the regular power connectors, including standard solar panel power connectors.

Although the connection module provides a quick and safe way to connect the solar panels, the interconnection board wiring layout makes it difficult to configure the panels into various setups. Each module is capable of configuring the way that its electronics are connected to the experiment circuit, either in parallel or in series or as a combination. To connect multiple solar panels, two as per the prototype specification, each unit has to be configured to allow multiple connection settings.

However, allowing this makes interconnection of the units difficult, and introduces a risk for mistakes including the short-circuiting of the solar panel pair resulting in large short circuit currents, outside of the influence of the protection circuits.

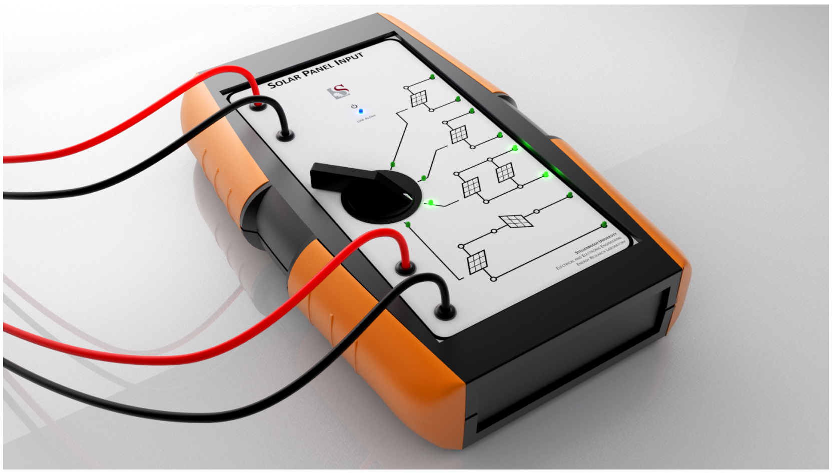


Figure 5.16: A variation on the input module from the first prototype. *(Rendering by Author)*

An alternative solution is pictured in Figure 5.16. In this unit we connected the two panels into a single combined input unit. The wiring could then be done inside the unit, and the user only had to select the appropriate configuration. But this approach also yielded several problems. Few rotary switches can handle the amount of current required, with enough terminals and switch positions but small enough to fit inside the profile of the selected grip-case. The rotary switches also do not completely disconnect before moving onto the next position, causing a momentary short circuit.

5.2.8 Experiment Specific Modules

Certain practical experiments will require speciality modules to perform specific tasks. Given the practicals we used as an example case, we needed a module that students can use to simulate the role of a maximum power point tracker, but that would allow them to set the duty cycle manually. To this end we designed a Manual Duty-Cycle Step-Down Converter Module (shown in Figure 5.17) that connects an external load resistor to the solar panels through a buck-boost converter with a manually selectable duty cycle.

To get the maximum power transfer from a solar panel, the panel has to be operated at its peak power point. By setting the duty-cycle on the buck-boost converter the user is able to move the operating voltage point of the solar panel, which in turn affects the current point, and change the resulting output power.

This module has a voltage and current indicator panel for both the input and output side, as well as a central circular indicator to show the current duty

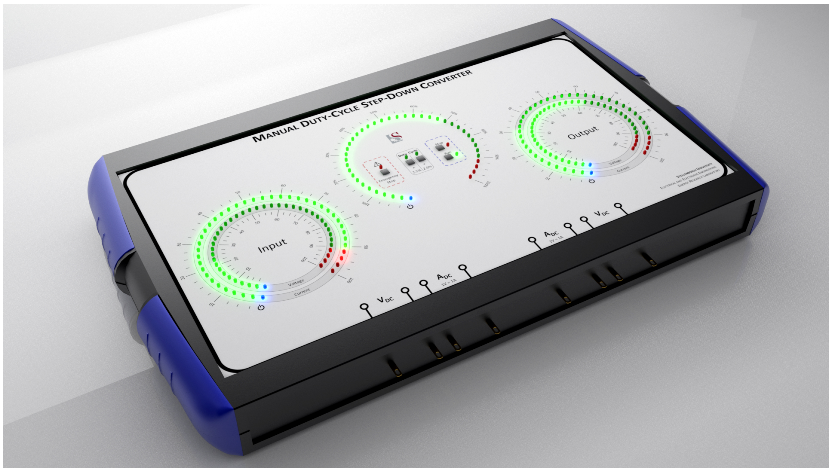


Figure 5.17: Buck-boost converter from the first prototype used as a programmable maximum power point tracker. *(Rendering by Author)*

cycle selected by the user. The module also has an *emergency stop* button that disengages the module from the circuit. The emergency button differs from the stop button because the latter will first ramp the unit down to avoid high-current conditions when disengaging the load and the solar panels.

This module, similar to the measurement modules, has manual measurement pins at the bottom, allowing the user to observe the values directly, using external equipment.

5.2.9 Additional Modules

The measurement, protection, connection and experiment modules discussed so far will allow the student to conduct the experiments of the example practicals. However, there are many more modules that can be added to enhance the functionality of the system. During the initial prototyping we identified several other modules that could be added to the system. We divided them into *experiment tool modules* and *education support modules*.

However, one of the major drawbacks to the inclusion of more modules is the space limitation on the interconnection board, which we discuss in greater detail in §5.2.10 when we review the first prototype.

Experiment Tool Modules

The experiment tool modules support the development of more complex practical experiments by enabling the inclusion of advanced measurements. The experiment tool modules are specific to a single set of experiments, whereas the measurement modules (discussed in §5.2.5) can be used in any experiment. We identified the experiment tool module type using grey corner markers.

The additional experimental tool modules we identified were to support the solar energy practicals. The proposed modules are:

- an irradiance measurement module,
- a weather station module,
- a solar tracker module,
- and a panel and ambient temperature measurement unit.

The modules would serve to connect the external systems, such as a weather station or a solar tracker, to the interconnection board to allow the student to interface with that piece of equipment.

Education Support Modules

To support the student's practical education, we saw the need for a range of modules that work in a supervisory capacity to monitor the student. Such modules would be indicated by using brown case markers.

Again, the size limitation identified earlier places severe constrains on the addition of such modules.

5.2.10 Review of the First Prototype

The first prototype was a chance for us to explore the challenges in designing a system for practical engineering education. We used the solar energy practicals of ES414 as an example, resulting in a very broad set of non-specific requirements. The limited starting requirements allowed us to focus on the problem in the general rather than the specific sense.

Given the vague requirements it is difficult to say when a design has been completed. In this specific instance we realised that the type of system being developed was not sustainable, and that many of the design choices would cause problems if the system were to be implemented. We stopped here, identifying the various problems and successes of the design, and used this in the development of a second prototype.

Problems with the First Prototype

There were various problems with the first prototype. The most significant problem is that the system is too big. The interconnection board measures 700 mm by 1400 mm, with a height of 220 mm. This makes that unit difficult to carry, which is needed to move the unit outside. Furthermore, the system has a lot of additional equipment that must be carried and installed, including the 12 modules, two solar panels, load resistor and battery packs.

Size is not only a problem for transportation and installation but also for storage. Although most of the modules can be reused in other practicals, the interconnection board as well as some of the experiment specific modules cannot. The external equipment, namely the solar panels and load resistor, also require storage.

The interconnection board also limits the adaptability of the system. Currently the board can only accommodate 14 modules, and cannot realistically be made any bigger. This restricts both the complexity as well as the variety of experiments that can be performed on a single interconnection board.

The relatively small module cases and the thickness of the interface board also place severe limitations on both the electrical components that can be used, as well as the supported electricity levels. Switching to three-phase power would require a complete rewiring of the interconnection board as well as the adoption of a new connection plug for the modules. And since the interconnection board and modules are sealed, heat dissipation and energy capacity of the components contained inside them become problematic.

Successes of the First Prototype

A number of elements from the first prototype were successful and must be incorporated into future designs. An important one is the clarity of the system's user-interface and physical design. Testing the interfaces on students, using full-scale printouts and mock-ups, allowed us to see elements of the designs they were unhappy about.

The colour coding of the module types provides a clear way for new users to read the board. And the user-interface on each module mimics existing systems enough so that it is possible for users to adapt to the new system quickly. The soft-fail limiters also help to ensure that mistakes made by the user is not catastrophic.

How errors are handled by the design is a crucial element of developing a system for use by students. A successful element of the first prototype is that it is a *forgiving* design — one that tries to help students avoid mistakes, while also minimizing the negative consequences in the event that a mistake is made. One way to achieve this is through *constraint design*, which limits the actions that can be performed on the system so as to limit possible mistakes. The proposed implementation of a solar panel configuration selector is a prime example of this. This is further supported through *design consistency*, ensuring that the elements of the various modules that function the same, are also expressed in the same way.[Lidwell et al., 2003]

The Next Step

We needed to focus on developing a system that can be used by both the students during practicals and the researchers during experiments. The design must also be more universal, so that a single system can be used for more practicals. Finally the new prototype will have to include a data interface.

5.3 Second Prototype

5.3.1 Overview

The second prototype also has a modular approach to the system design, but unlike the first prototype the modules are no longer stand-alone units but rather only provide the functional part of the circuit with the data and user interfaces provided by a dedicated module.

We split the system into three sections, namely the *backplane interlink*, the *system modules* and the *power supply*. A diagram of the proposed design is shown in Figure 5.18. The backplane interlink is similar to the interconnection board in that it is used to connect the various modules as well as to provide the power transmission circuits.

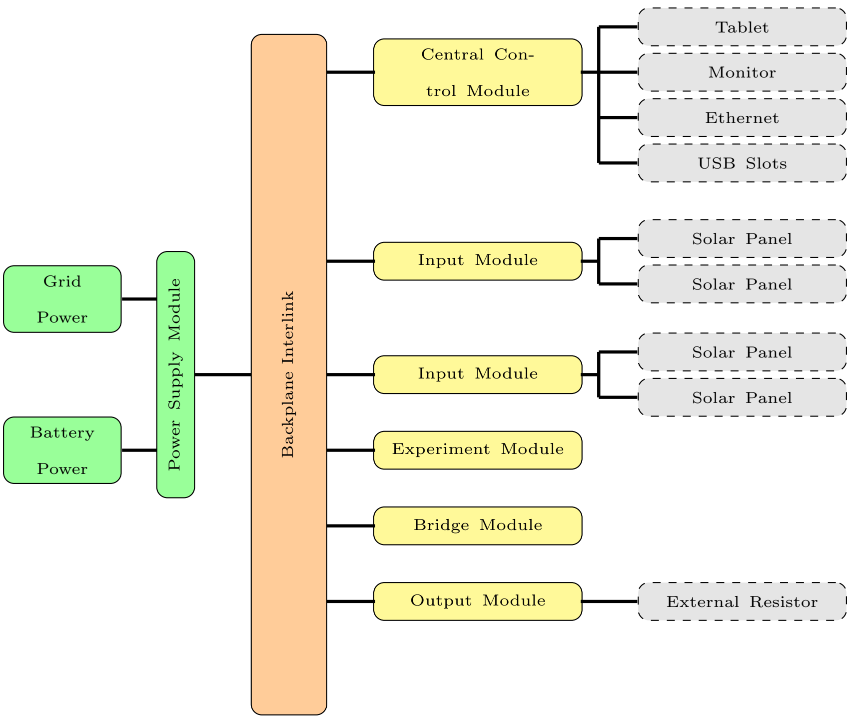


Figure 5.18: System diagram of the second prototype.

To standardise the system we chose to house it inside a single three unit high standard 19 inch computer sub-rack enclosure. We refer to the sub-rack enclosure with the backplane interlink and power supply as the shell, which is then populated by various modules to make a completed system. The user-interface has also been moved away from the rack to an external computer monitor, keyboard and mouse that serve as the interface with the system.

The system provides connections for a *control module*, a *power module* and *five general experiment support modules*. The system is designed to be read from left to right, starting with the power module, then the control module, and then the five experiment support modules.

5.3.2 The Enclosure

Figure 5.19: The second prototype system, free standing with installed modules. *(Rendering by Author)*

The enclosure is an aluminium and steel Schroff Interscale-M perforate subrack enclosure, with a height of three rack-units[1] and a depth of 310 mm. (The free standing system with installed modules is shown in Figure 5.19.)

To allow the unit to be used in the field, the rack is installed inside a flight case, and includes a 19 inch touch screen monitor. Carry handles make the unit easy to transport and the rugged design of the case protects the equipment. (The complete flight case with installed equipment is shown in Figure 5.20. The load resistor, discussed in §5.3.7, is installed below the main system.)

5.3.3 The Backplane Interlink

The Backplane Interlink serves four functions: to provide the transmission lines to connect the various experiment support modules together, to provide power from the power supply to the modules, to provide a data bus to connect the experiment support modules to the master computer module, and finally to provide a physical

[1]A single rack unit is 44.50 mm high.

Figure 5.20: The second prototype system in a flight case with all the equipment installed. *(Rendering by Author)*

address to each inserted module to allow its addressing in the system. (The backplane interlink is pictured in Figure 5.21.)

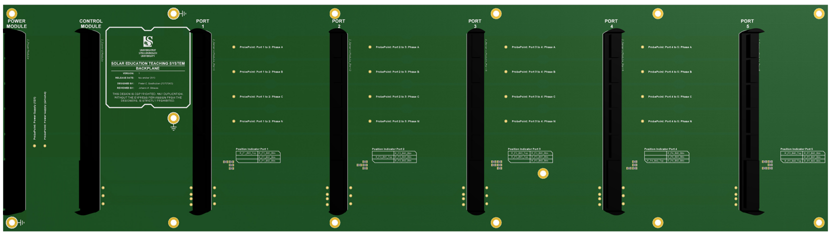


Figure 5.21: Top view of the PCB for the backplane interlink module. *(Rendering by Author)*

However, it is important to understand that the backplane does not provide active circuitry, but only wired links between the various modules and the power supply (with the exception of the resistors provided to identify the address of an experiment support module).

A schematic view of the connections provided by the backplane interlink is shown in Figure 5.22. The *Control Module* and the *Power Module* will be discussed in §5.3.5 and §5.3.6 respectively.

Power Transmission

In the first prototype we used a network of wiring located inside the interconnection board to connect each experiment support module to the next. The board was also limited to a two wire DC circuit with a ground connection pin. To accommodate a wider array of practicals, we designed the second prototype to have

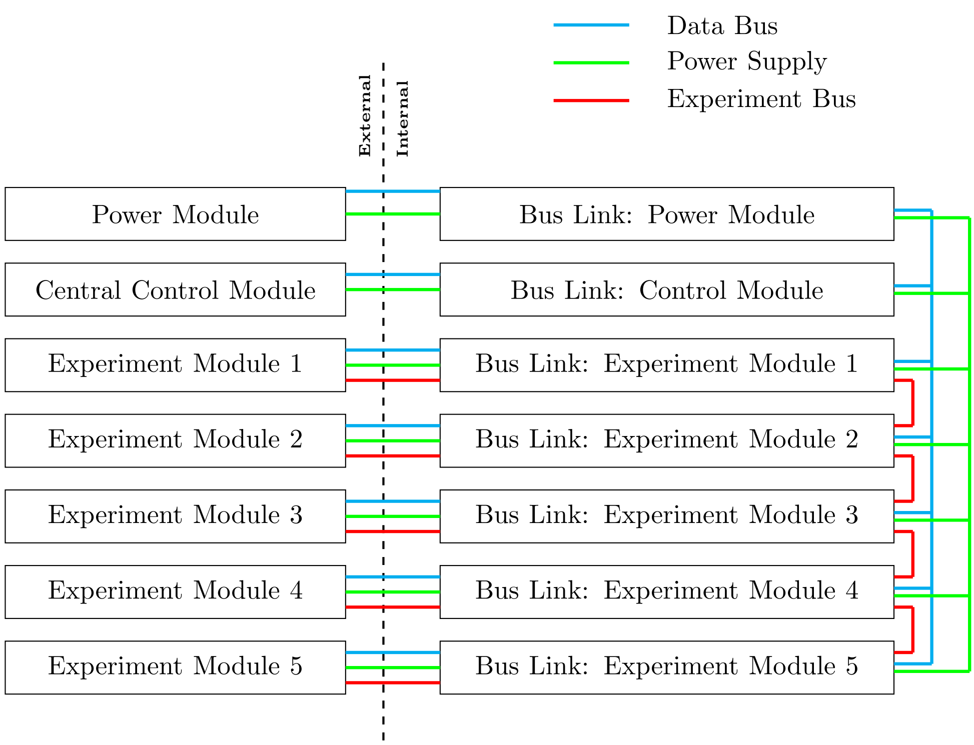


Figure 5.22: Schematic overview of the backplane interlink module interface.

a four wire transmission network with a ground connection pin. Except for the ground pin, which is always connected, the rest of the phases break at each module slot to allow the module to configure its own connection to the experiment network. (See Figure 5.23.)

The wire labels are intended for a three phase system, but the names are merely identifiers and can be changed in the control software depending on the type of modules inserted in the various module slots. The transmission channels can also be combined to increase their current capacity. Thus for our system, which only has DC power, we will combine the a-phase and b-phase into the positive conductor and the c-phase and neutral-phase into the negative conductor.

The power transmission tracks are 10 mm wide, and are located on both the front and back of a two sided printed circuit board. Assuming a summer ambient temperature of 40°C and allowing for a permissible rise of 20°C, then on a 10 mm, 35 μm copper track we get a maximum permissible current of 17.22 A_{DC}. Using the current specifications in §5.2.3 we need a current capacity of 21.4 A_{DC}, and since we have two tracks per phase as well as two phases per pole, for the DC circuit, we only need a quarter of the maximum current capacity per track, or 5.35 A_{DC}, which is well within specification.

To confirm the theoretical prediction we constructed a demonstration board with various trace widths. (The board is pictured in Figure 5.24a.) The first

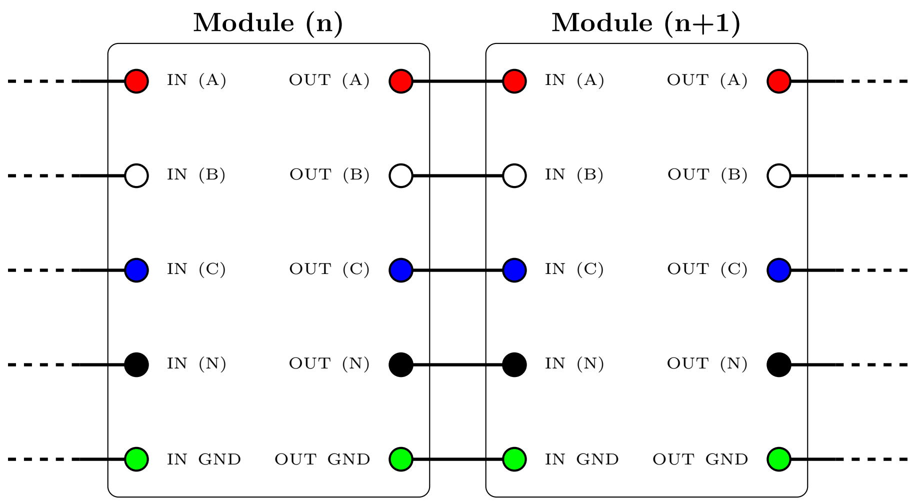
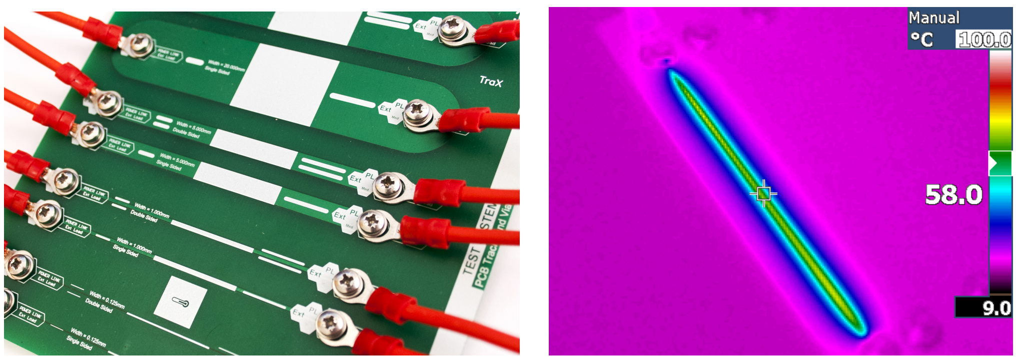


Figure 5.23: Example of the power transmission module interconnection from the second prototype.

trace has a width of 0.125 mm and is single side only. The ambient temperature during the experiment was 18°C. We applied a 4 A_{DC} current, and measured a temperature rise of 40°C as is shown in Figure 5.24b. This is a current capacity four times higher than the predicted value. However, it is important to note that the heat radiated by the PCB track is not confined only to itself, but rather will affect nearby tracks. So when calculating trace widths one has to increase the minimum clearance distances to accommodate for this.



(a) Demonstration board used for PCB trace current capacity testing.

(b) Infrared image showing the PCB track during a current load of 4 A.

Figure 5.24: Demonstration confirming the theoretical PCB trace current capacities. *(Photo Credit: Author)*

Another important observation is the way in which heat dissipates into the circuit. The large connection points, in this case a via with a M3 screw linking the external wire, provides an area of increased heat dissipation, resulting in an uneven radiation pattern across the track, as is shown in Figure 5.25.

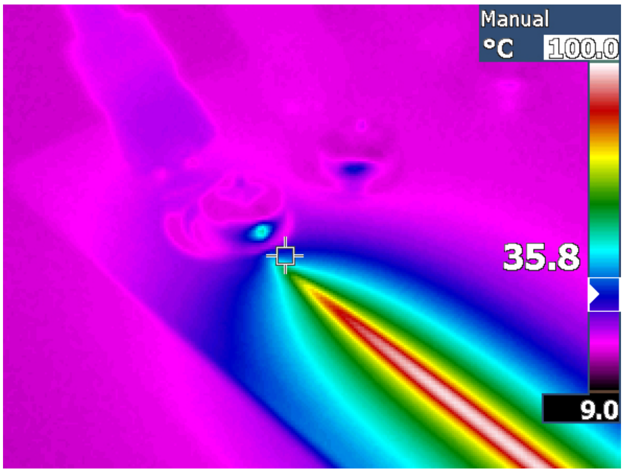


Figure 5.25: Demonstration of the uneven heat dissipation pattern on a PCB track in the presence of a connection terminal. *(Photo Credit: Author)*

Power Supply

The system has a dedicated power supply, located behind the backplane interlink in the shell. (The power supply is discussed in more detail in §5.3.6.) The backplane links the various modules to the positive 12 V_{DC} power supply through an additional 10 mm, single-sided Printed Circuit Board (PCB) track.

Data Bus

To allow the experiment support modules to communicate with the control module, the backplane has a parallel 29-line data bus. We will explain the data bus in more detail when we discuss the control module, in §5.3.5.

Experiment Support Module Addressing

It is imperative that each module knows the address of the slot it has been plugged into. To do this three pins on the 32 pin data connector are used as a 3-bit address — grounding the lines to indicate a logic zero and raising the line to 5 V_{DC} for a logic one. When an experiment support module is plugged in, the on-board processor reads the three pins to identify the module slot it has been inserted into.

5.3.4 Modules: General

The modules are 270 mm long, 100 mm high and have a set of connector tabs 8.7 mm deep at the end. The modules have an aluminium front plate that serves as the grip to insert and remove the module into or out of the shell, and as the limited user-interface to indicate the modules title as well as its current status.

Internally the module is protected by a steel frame and a perspex cover, to protect the electronics when the module is not inside the system. (Figure 5.26 shows a demonstration unit.)

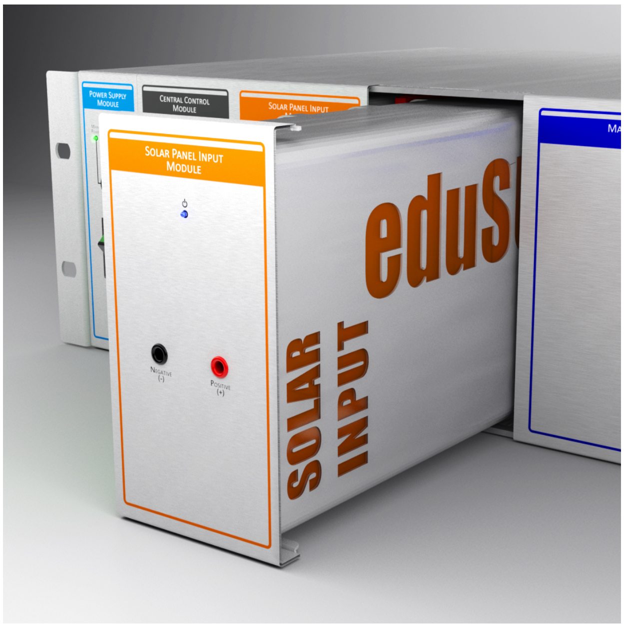


Figure 5.26: A generic module from the second prototype showing the general structure and protection features. *(Rendering by Author)*

The modules are categorised according to the interface with the backplane. The three types are:

- the control module, which controls all the modules and provides the links with the external user-interfaces devices,
- the power-module, which links the power supply into the power bus on the backplane,
- and lastly the general experiment support modules, which provide the various functions required to conduct experiments during the practicals.

5.3.5 Module: Central Control

The central control module interfaces with all the other modules, processes the information, displays it for the user and handles the control instructions sent back to the separate modules. (The system interface with the backplane is shown in Figure 5.27.)

A detailed system's diagram is shown in Figure 5.28. The module has two computing platforms, namely the motherboard and the Raspberry Pi (rPi) Small Single Board Computer (SSBC). The motherboard is an 8-bit processing platform

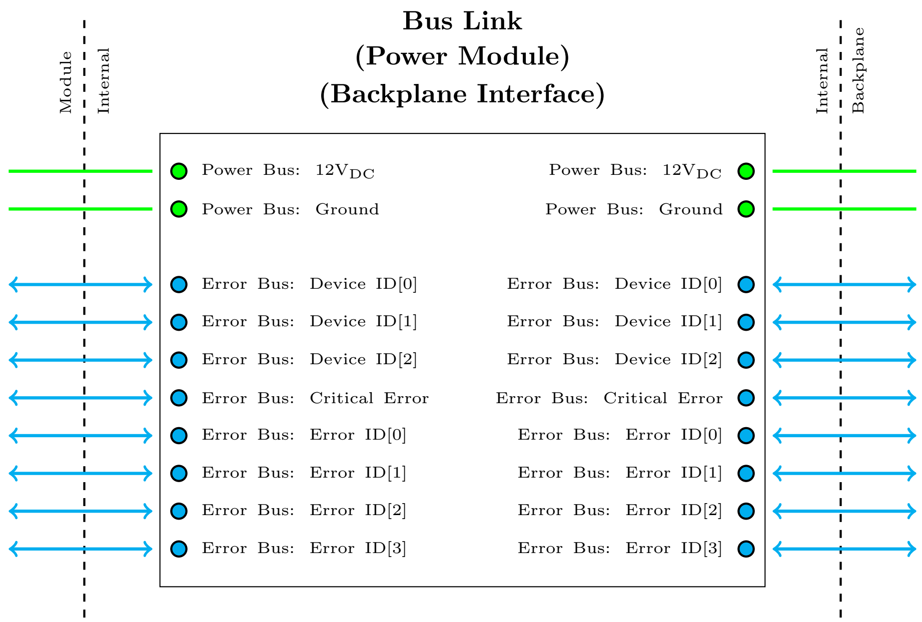


Figure 5.27: Interface overview of the power module connection to the backplane.

that is responsible for interfacing with all the modules in the system. Information it collects is sent to the SSBC for display to the user, and instructions to the modules from the user are sent back to the motherboard for execution. A data buffer provides a temporary storage space for measurements, ensuring that the system will not lose measurement data if the SSBC is busy.

The SSBC connects to various break-out boards. These break-out boards include:

- HDMI interface to connect a screen,
- USB connection to allow users to connect a flash drive and download experiment data,
- another USB connection, linked to a Wi-Fi dongle that can create a Wi-Fi network allowing users to connect to the equipment using a computer, tablet or smart-phone,
- RJ-45 ethernet jack to connect the system to a wired network,
- a front heads-up-display that can indicate basic status information,
- and finally a front HUD that displays the status of the error bus.

Modular Computer

At first we wanted to use an 8-bit microprocessor on its own. This unit would communicate with the system modules and provide a user-interface to the student.

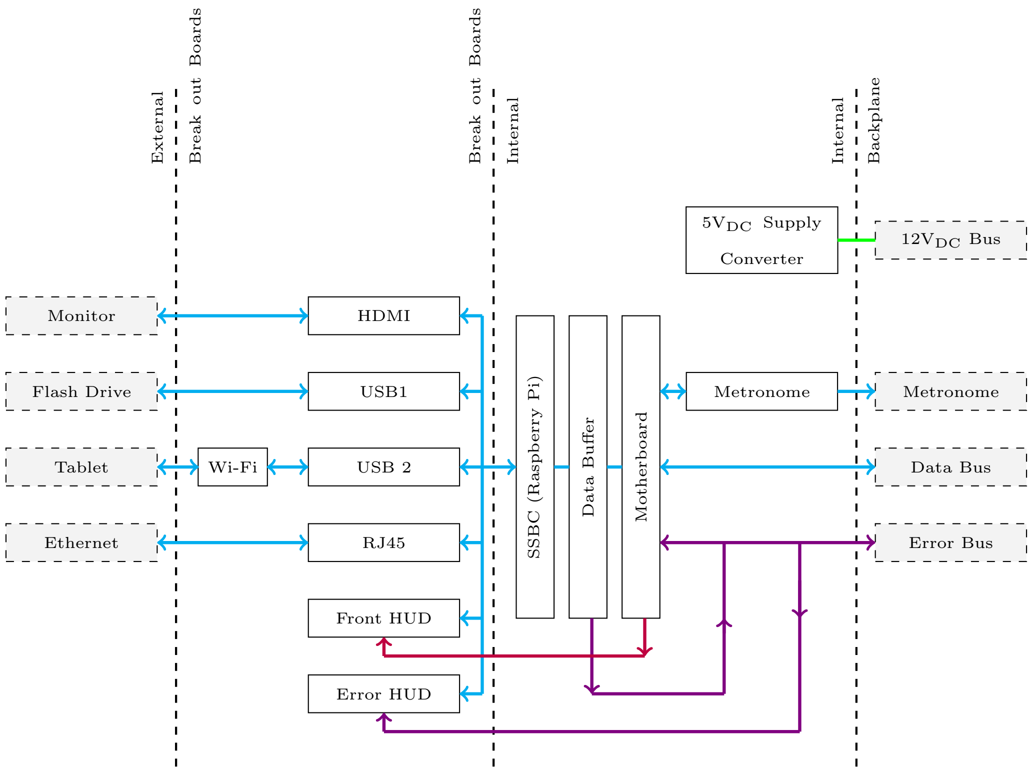


Figure 5.28: System diagram of the central control module.

However, we soon realised that the requirements we had for the user-interface were too much for a stand-alone 8-bit processor.

We wanted network connectivity and to allow the user to interface using a regular computer monitor, keyboard and mouse, as well as to load data onto USB flash memory devices. Even though it is technically possible to implement most of this functionality with an 8-bit processor, we would have to develop most of the interfaces ourselves.

This turned our attention towards using a system that has both the interfaces installed as well as an operating system to handle them. There are various small single board computers (see section §7.2.1 for a more detailed discussion) that have come on the market. We chose to use the Raspberry Pi. The unit provides High-Definition Multimedia Interface (HDMI), USB and network interfaces as well as an implementation of Linux that can be used to develop more sophisticated and complex software. Another distinct advantage of using an operating system is that it is capable of process load-balancing, which helps to ensure a higher quality of service from the device.

We still decided to use an 8-bit microprocessor system to interface with the system modules. The motherboard sub-system serves as the principle controller of the control module and is responsible for maintaining the communication interface to the various modules, as well as collecting data from them and returning instructions to them. A First-In-First-Out (FIFO) buffer stores measurement data if the microcomputer is temporarily unavailable or busy.

Communication

The motherboard communicates with all the other modules using Serial Peripheral Interface (SPI) communication. There are three distinct data buses, namely the *principle data bus*, the *error bus* and the *metronome*.

The principle *data bus* is a 16-bit wide bus that communicates instructions and measurements to and from the various experiment support modules, as well as connect to the power supply system. The system uses a hybrid SPI communication interface, with five *SPI Talk Lines* that are normally high and are pulled down to indicate the module slot that the processor needs to communicate with. The address indicator discussed earlier is used by the various modules to identify its their addresses in the system.

The *metronome* forms part of the communication bus, and is a way for the system to synchronise measurements across the various modules. A synchronisation pulse and a timecode is broadcast at a regular interval. This broadcast is sent to all the modules, but engaging all the SPI talk lines simultaneously. The experiment support modules use this synchronising pulse to enable their respective sample and hold circuits, and then encode the measured results with the provided timecode before sending them back to the control module. This ensures that all the measurements are taken at the same time, allowing for the accurate measurement of phase effects. Although not a critical requirement for DC measurements, it is crucial when working with AC systems.

The *error bus* is a collection of eight lines that are linked into every module through a tristate buffer. The lines are normally held in a logical high, and can be pulled down by any of the modules should an error occur. The principle of the error bus is to ensure that all the modules are instantly aware of any problems inside the system and can respond accordingly.

The error bus is divided into three sections: three lines to indicate the device causing the error, a single line to indicate critical errors, and four lines to indicate a non-critical error. Since the non-critical bus component is 4-bits wide, there 15 possible error codes that can be signalled, plus the all-clear. It is important that the error response of all modules, regardless of the developer, is consistent. Since not all the error codes will be assigned from the start, several modules will be developed that will have to be updated as new codes are introduced. If a module receives a code that it does not know, the default action should be to disconnect itself from the system until an all clear code has been broadcast through the data bus.

5.3.6 Module: Power Interface

The power interface is a two-part solution, namely the power supply itself and the module that interfaces with the power supply as well as linking the power to the backplane. The power supply is a standard switch mode computer power supply. This means that the unit is easy to source, install and replace.

The power interface module is located at the leftmost slot on the backplane, and feeds the power from the power supply into the backplane. The module also contains a power button to allow the user to switch on the system.

5.3.7 Module: Experiment Support Modules

In the first prototype we proposed a manual duty cycle step-down converter, as well as input and output modules to connect the external solar panels and the load resistor. Staying with these, we now address their designs in the second prototype.

The first variation between the experiment support modules of the two prototypes has to do with where measurements are taken. Rather than having dedicated measurement modules, it is now incorporated into the input and output modules, as well as the manual step-down converter.

The Solar Panel Input Modules

Rather than connecting two solar panels on a single module, as we did with the first prototype, we now only connect a single solar panel per module. The module has a simple front-plate with two slots for the positive and negative terminals of a solar panel. Internally the solar panel is routed to the backplane experiment bus using a network of ten relays.

The relays are controlled by the module's motherboard, which in turn is directed by the central control module. Since the circuit selection is done through a computer interface, and not manually as with the first prototype, there is no risk of accidental short-circuits or faulty connections, and multiple input modules can work together to create more complex circuits.

The Output Module

The system still needs to connect to an external load resistor. In keeping with the modular 19 inch rack design, the load resistor is installed in a similar sub-rack to the main system, but only a single unit high.

The problem is to connect the unit to the main system. There are two connection options, namely to connect the resistor through a dedicated module in the front or to connect the load resistor directly to the experiment bus on the backplane. This is an interesting problem, because it poses another question: if we have more modules than can be accommodated in a single rack, how will we expand the system?

For the purposes of our solar energy practicals example we will not likely run out of space, although it is important to note that some experiment support modules (such as the manual duty cycle step-down converter) may require more than a single slot due to the size of the internal components. If we consider the experiment support modules that will be required during a practical in electrical machines, we realise that we will have to have more than one sub-rack.

It is still technically possible to connect the experiment power bus on the backplanes of the various subsystems together, although the data bus is not able to be connected this way, as the communication platform is for inter-chip communication only and will not be sustainable over longer distances.

This limitation is one of the biggest problems with the second prototype, and will become one of the key driving principles of the third prototype.

For the purposes of completing the second prototype, we decided to use an experiment support module to connect to the external load resistor.

5.3.8 Support Modules

We also developed a bridge and a debug module. They perform support functions that are not directly related to the execution of a practical.

Since the experiment power bus is broken at each module slot, it is necessary to bridge it if a module is not installed in a particular slot. However, if for example only three modules are required, they can simply be installed in the first three slots and it will not be necessary to bridge the last two slots. The bridge will most regularly not be used as a stand-alone module, but will rather be incorporated as a PCB (shown in Figure 5.29) into modules that take up more than a single slot and require the remaining slots to be bridged.

When used as a stand-alone module the PCB can also be connected to an LED on the front panel, to indicate if the bridge is receiving power from the bus and thus is plugged in correctly.

Since the backplane is located deep inside the system, it is difficult to make any measurements on the buses. To support developers, as well as staff servicing the unit, we developed a debug module (shown in Figure 5.30) that slots into the backplane, but protrudes out of the front of the system, providing access to all the bus values.

The descriptions provided on the PCB are intended to allow users easy location of the required circuits without the need for documentation and additional pin-outs. The board also provides a header to connect directly to the data bus, enabling the development of dedicated testing equipment. (A detailed view is

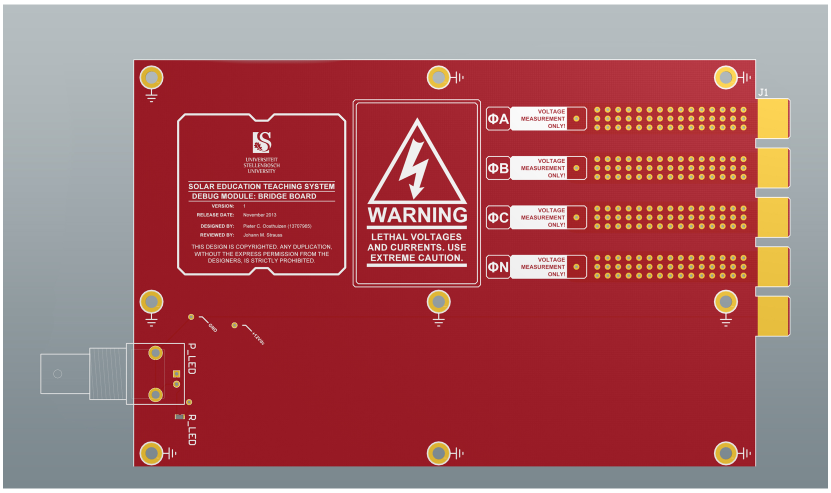


Figure 5.29: Top view of the PCB for the bridging module. *(Rendering by Author)*

Figure 5.30: Top view of the PCB for the debug module. *(Rendering by Author)*

shown in Figure 5.31.) A wooden handle is attached to the four mounting holes on the front of the module, ensuring it can be safely connected and disconnected while the buses are active.

5.3.9 Review of the Second Prototype

In many regards the second prototype is a significant improvement over the first. The system is much more adaptable, compact and portable and has a control interface and interconnection platform that allows the units to communicate as well as provides a system to manage the practical itself. (We will expand on the software in Chapter 8.)

The most significant change is the virtualization of the experiment system. Rather than each device providing output to the user with its own user-interface, the system has an internal data only link to the modules, and then provides a software user-interface. This not only allows a much more complex display but, by installing a web-server on the rPi, one is able to provide the interface as a website hosted natively on the practical education system itself. Users can now connect to the unit using a tablet, making the computer monitor redundant and

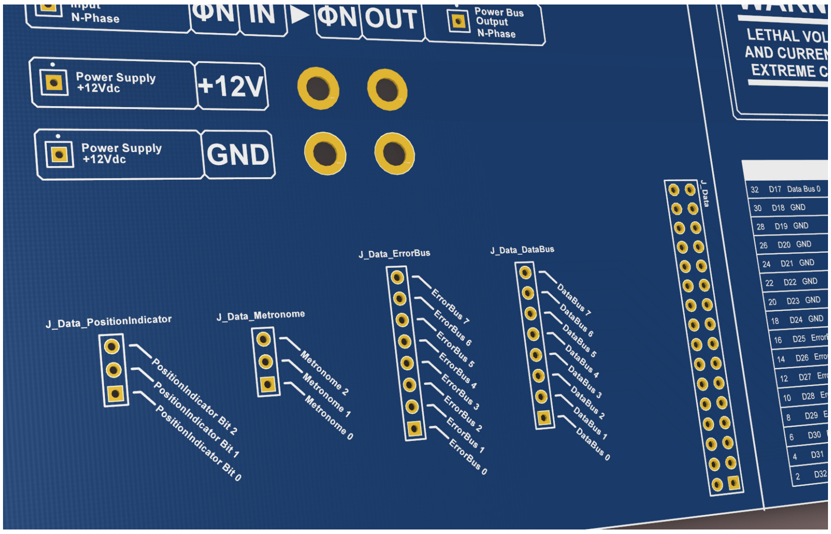


Figure 5.31: Detailed view of the debug module PCB indicating the explanatory markings. *(Rendering by Author)*

further decreasing the power requirements and mobility of the system.

However, there are still problems with this prototype which, we feel, makes it unsuitable as the basis for a framework. The most important issue here is the limitation on the expansion of the system. Even though the shell is considerably more adaptable than the previous system, it is still limited to a single unit, and to the current capacity of the printed circuit tracks. Even if two systems could be linked physically, the way that the current data link is designed makes it unsuitable for more than five units. This is a function of both the addressing technique as well as the bandwidth and lack of robustness of the communication system.

The experiment support modules also pose a problem: since they cannot be used in a stand-alone environment they are of little use to researchers who wish to expand its use for experimental purposes. Although the researcher could develop a custom control module dedicated to experimentation, this puts us back in the position of having to develop multiple shells.

Another problem is that all the experiment support modules are located in close proximity to each other. During the development of the prototype it became clear that it may be advantageous to be able to have some of the equipment close by and other at remote locations. This is especially the case for solar-photovoltaic equipment. In the current setup we are limited to equipment that the student can carry to the test site. Subsequently, if we want to start using solar panels on heliostatic mountings the students would have to move the equipment to the roof of the building and perform the entire practical there.

The Next Step

In the next prototype we will focus on developing a robust communication standard. Also, we need to ensure that the system can address the needs of all the involved parties. Currently the system functions as a practical education tool, but to the detriment of the requirements of the other users.

5.4 Third and Final Prototype

For the third and final prototype we expanded on the idea of a communication linked modular approach. In the second prototype we proposed the idea of modules, each one with its own motherboard that connected with the controller module over a custom data protocol using a chip-to-chip connection interface. But it is challenging to develop a high-speed and robust communication bus, and this meant that the interconnection between modules was slow and could only occur in very close proximity (typically not outside the backplane itself). The addressing on the bus also meant that the bus could only support a very limited number of modules.

So, we decided to investigate the use of an Ethernet based approach. By making each module a stand-alone network entity we could make use of existing network infrastructure, not only to increase the number of units linked together but also to remove the limitation on where the units are located relative to each other.

This development led us to questioning the role of the control module itself. Since each module would be able to function independently, there was no more use for a control module for the management of the low-level system's operation. Rather, the requirement was to increase the level of sophistication of the system managing the practical itself. This resulted in the development of the *Engineering Practical Main Computer Module.*

We also developed several other modules that are designed to support the system rather than the experiment itself. In terms of the experiment support modules, we combine the entire solar energy practical experimental setup into a single sub-rack module. And, crucially, this new *Dummy Load* module can be used for research just as easily as to present practicals.

We will discuss the third prototype in more detail in the following three chapters. In Chapter 6 we briefly discuss the inter-module communication, followed by a detailed discussion of the hardware design and development in Chapter 7. Finally we conclude the design of the prototype with a discussion of the software front-end in Chapter 8.

5.5 Chapter Summary

To understand the challenges of designing a system for practical engineering education, we decided to approach the problem through prototyping. Through the course of this chapter we have done a detailed development of two prototypes, and laid the groundwork for the third and final prototype that will be discussed in detail in the subsequent three chapters.

Through the prototype development we have not only evolved the system itself, but also expanded our thoughts on the requirements for such a system. We have also discussed some of the technical requirements and the detailed design principles that are needed to develop a system which is both electrically functional as well as suitable and simple to the end-user.

Chapter 6

Third Prototype: Inter-Module Communication Interface

6.1 Introduction

The communication interface is a crucial element of the third prototype. However, it is also a very complex element and requires careful consideration before it can be included into the framework. In this chapter we will investigate the use of the new Ethernet based communication system, discussing the benefits as well as the problems with this approach, but mainly identifying the considerations that will have to be made in order for it to be used effectively and efficiently.

The Ethernet based communications approach allows the system to be diffused into a collection of stand-alone modules that can be installed in remote locations, and used in isolation while still allowing the user to connect them together to form larger systems. This increases the modularity of the system dramatically.

By the end of development on the second prototype (detailed in Chapter 5) we came to realise that the standard industrial and chip-to-chip communication protocols would not be capable of meeting our requirements. We needed a system that was capable of performing experiments, be it for practicals or as part of a research experiment, both inside the laboratory as well as at remote locations. We also needed a system that could fulfil some of the other systems requirements that we had identified in Chapter 3 and Chapter 4, such as for class demonstrations.

Although there are a fair number of systems that do use protocols and bus-standards such as MODBUS, RS-232, I^2C, and SPI to great success, they are limited in many ways — most notably the limited bandwidth, implementation complexity and relative lack of installed infrastructure.

Our proposed solution is to use the Internet protocol stack — the collection of protocols and standards that facilitate data transmission of all kinds on the Internet. There are two main reasons for choosing this protocol, the first being the ubiquitousness of LAN infrastructure and, second, the fact that the stack (if implemented correctly) shifts the burden of communication fidelity from the application, transmitting and receiving the information, to the processes and hardware lower in the stack.[Goralski, 2009]

A key difference between our proposed system and those presented in other digital laboratory systems (including several professional laboratory solutions) is the point of network connectivity. The design currently proposed in the literature has a single point of network connectivity, normally hosted through some form of a controller, as can be seen in the diagram in Figure 6.1. Theoretically, the connection between the various modules and the controller can be in any format, but we noticed that the majority of newer systems tend to use USB, since it is a common interface technology that is widely available. Our proposal is to move the point of network connectivity to the modules themselves, as shown in Figure 6.2. This way each module connects directly to the LAN, and the system controller is just another node on that system. [Aydogmus and Aydogmus, 2009, Buiu, 2009, Aktan et al., 1996, Deniz et al., 2003]

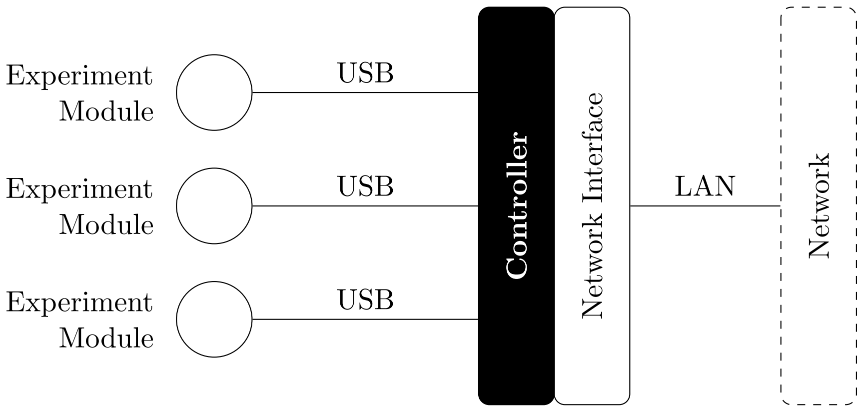


Figure 6.1: Network connectivity model as proposed by current literature.

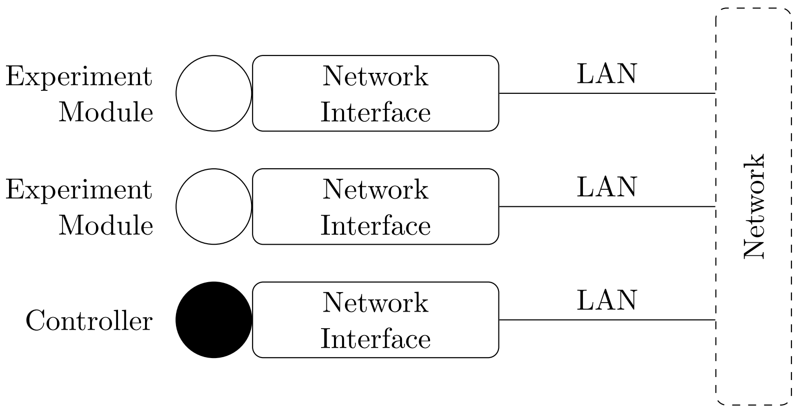


Figure 6.2: Network connectivity model proposed by this study.

This solution is possible because of the advances in microprocessor technology, and the implementation of complete operating systems that move away from the traditional 8-bit micro-controller environment. These SSBCs (see §7.2.1 for more information on the SSBC) already have implementations of the Internet protocol stack installed. The Linux operating systems available for use on these units provide the tools to configure and use advanced networking features, including network monitoring, security and encryption, as well as software to negotiate with firewalls which have become commonplace at universities.

Another advantage of this approach is that the dedicated controller unit is, technically, not required. Since each module is connected to the network individually it is possible for any user sharing the same network to connect to the particular module directly. When assembling a practical education platform the controller module would be loaded with software that would enable it to manage the practical sessions, experiment data, administration as well as the screens and controllers to provide users with feedback and methods for input, but it would still only communicate with the various modules over the network.

Since the modules can then link via the network, the physical location of the various modules also become irrelevant, since the system is only concerned with the network connection between them. This allows a controller being used by a student, located on the laboratory workbench, to use the motor equipment modules right next to it or to switch over and use the equipment on the laboratory roof, without any change in the physical setup.

Similarly, any user could interface with the controller, allowing a lecturer in the classroom to use the system and demonstrate on it, with the students seeing the same output as if they were in the laboratory.

The network linked model also means that the entire laboratory is on-line; at least linked to the Intranet of the university. This allows the development and use of monitoring applications that permit the lecturer to monitor all the setups simultaneously.

In the next sections we are going to discuss the impact and requirements of the interface on the application layer of the protocol only. As each module will be required to implement the full Internet protocol stack however they see fit, we are concerned with the application layer, where information is encoded for use by the systems themselves, rather than by the network infrastructure.

6.2 The Suitability of the Internet Protocol and Networks to the Practical System

In this section we look at various design considerations that have to be made when using the proposed network connection topology. Several factors must be considered when using an Internet Protocol (IP) network to measure and operate on equipment, namely: *bandwidth*, *latency*, *security* and *safety*.

6.2.1 Bandwidth

The bandwidth of a network determines the amount of information that can be transferred between two systems in a given time. A problem with installing systems such as ours on a general network is that the network infrastructure will not prioritise the traffic between the components of the practical education system above the traffic of the rest of the users on the network. Though it is technically possible to configure the switches to prioritise the traffic, our aim is to design a system that can be used without altering the network infrastructure.

We propose the following solutions:

- **Install and use sub-networks:** In cases where a number of modules will be used together, with or without a controller, these units can be grouped into a new private network with its own network switch. A single interface device can then connect the group of devices to the rest of the network. This will not only speed up local transfers between modules, but will also remove a significant amount of traffic from the larger network.

- **Scaled Real-Time Data:** In situations where a burst of data is required, the modules can be set to output down-sampled data to the user's computer, but store the big data burst for later download. This allows the user to still monitor the measurements in real-time, but at a much lower sample rate than being recorded by the module.

- **Controller Down-Sampling:** In a similar fashion to the way in which streaming content is adapted to different data-rates depending on the current connection, so too can the controller down-sample the data stream that results from all the various modules it is interacting with. This would mean that a lecturer in a classroom that has a poor connection to the network will see a reduction in update frequency, but will still be able to demonstrate the experiment to the class.

6.2.2 Latency

The latency of a network is the time between a stimulation and a perceived response. A high latency can cause two problems: slowing the perceived reaction time of the system and, secondly, inhibiting control commands and alarm signals from reaching the various modules fast enough, thus creating a safety risk.

It is possible to configure the network to prioritise the traffic from certain devices, and even from specific protocols on the network. But, as with the bandwidth requirements, a system should preferably be operated without the need for changes in the institution's network infrastructure.

The latency is, for the most part, a property of the network itself and very little can be done from a system's perspective to correct a high-latency connection. Thus the solution is the mitigation of risk through proper management of high latency situations should they occur. This requires that the latency of the network is continuously monitored, which entails finding the latency between all units, but specifically between the controller and the units it connects to.

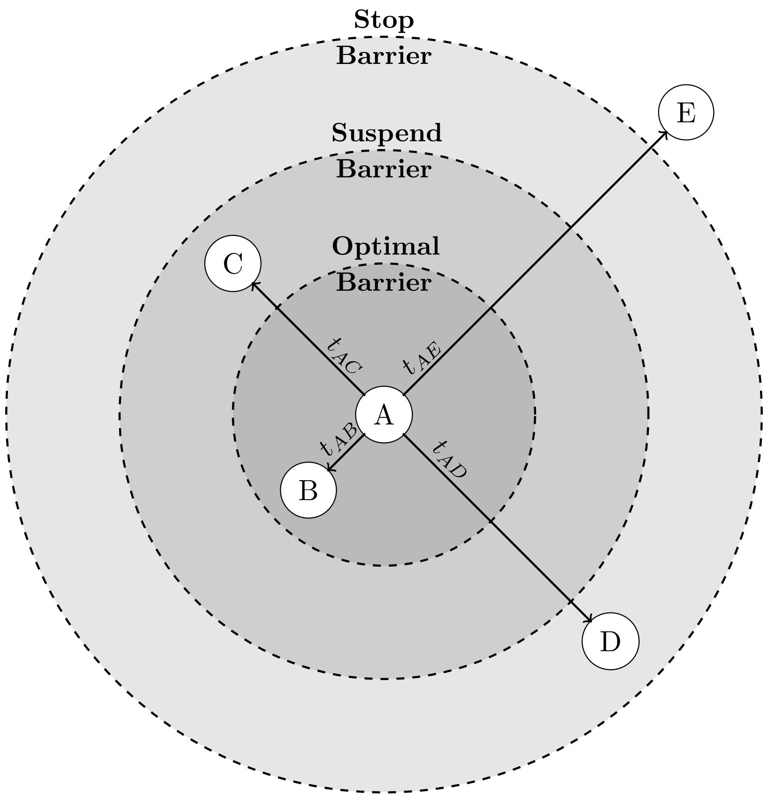


Figure 6.3: Latency graph, including action zones, from the perspective of a single controller node.

Knowing this, the units could be configured with a series of rules in order to handle high latency situations, as depicted in Figure 6.3. The diagram depicts a controller, node A, and four modules that it is communicating with, denoted nodes B through E. The latency of the communication to each module determines the node's distance, and is indicated on the vector. (The nodes are equispaced around the principle node for clarity) Any nodes that have a delay of more than that defined by the *optimal barrier value* are deemed to be lagged, or delayed, and the system will display a warning to the user. This allows the user to anticipate some slight delays when working.

If the delay time falls beyond the *suspend barrier value* then that node is deemed too delayed to be usable or safe and the equipment should be suspended temporarily until the network stabilises. However, if the time falls beyond the *stop barrier value*, the system will consider the network to be disconnected and will shut down all experiments. All modules will also do this calculation and follow similar steps.

All these rules define the quality-of-service, and can vary between various institutions as well as between individual users, depending on their preferences. For example, during a research session the system might be set to always keep measuring, regardless of networking conditions, in order to preserve data. However, this still poses a significant safety risk, as alarm and emergency commands cannot travel through effectively. To mitigate this, the designer of such a unit should add an emergency stop button directly to the module, and allow the continuation of service without a network connection only if the emergency stop button is present.

6.2.3 Security

Network security is an issue that cannot be ignored, especially if the system is opened up to the Internet, and even the university Intranet. Since students will be evaluated based on the data from these systems, it is also imperative that the information is encrypted and transmitted securely to ensure the protection of the students' information, but also to avoid the possibility of cheating.

Furthermore, since the system can be in direct control of physical hardware, it is important that the security systems safeguard against malicious attacks that can harm the users or the equipment itself.

The security of the system extends well beyond the Internet protocol stack itself, and includes the applications using it as well as the security of the operating system itself.

6.2.4 Safety

The safety of the system is primary concerned with the mitigation and management of risk during the remote operation of hardware in a laboratory, as well as the actions that the system must take to ensure safe operation and shut-downs in the event of an emergency. As mentioned in the previous sections, this is especially important in the event of a communications failure.

6.3 Chapter Summary

The Internet protocol stack would allow flexibility, enhanced modularity and integration with existing infrastructure. However, numerous issues need to be addressed, especially regarding the risks involved with networked modules when operating physical systems.

A significant amount of research and development will be needed to ensure the safe operation of the equipment and a stable network interlink. But the advantage of using the Internet protocol stack is that these changes all happen in the application layer of the protocol, which is software upgradable. This means that the first modules can be developed using a very simple Hypertext Transfer Protocol (HTTP) encoding with no security and, as the modules progress and more research is performed, they could be upgraded to include ever greater security features. This will allow the development to happen in a shared development environment, making it an ideal addition to the framework.

Chapter 7

Third Prototype: Physical Design

7.1 Introduction

The third prototype (depicted in Figure 7.1 as a stand-alone system with an accompanying touch screen) is a multi-module system linked together over a standard Ethernet connection. Continuing our use of the solar energy practicals from ES414 as a development example, we use this chapter to focus on the design of the hardware itself, leaving the discussion of the *network interface* and the *software front-end* to Chapter 6 and Chapter 8 respectively.

Figure 7.1: The third prototype system, free standing with a 30 inch touch screen monitor. *(Rendering by Author)*

Systems in the third prototype are grouped into independent units called modules. Each module connects to the network, and is a fully functioning system in its own right. We chose to develop four modules, matching the functionality of the second prototype but including the ability of modules to function as stand-alone measurement systems. The four modules are:

- the AC Power Supply (§7.3),
- the Practical System Controller (§7.4),
- the Network Link (§7.5),
- and the Dummy Load for Solar PV Systems (§7.6).

Besides these modules we will also be looking at the development of "mini-modules"— a term we use to describe sub-sets of a module that perform a single specific task. A mini-module allows developers to rapidly add functionality to their own systems by using standard designs for common components. An example of a mini-module is the AC Voltmeter. We will discuss mini-modules in more detail in §7.2.3.

The aim of this chapter is to provide information about the development of the practical education system design framework, by identifying challenges and possible solutions for the hardware components of the system. A limitation of our research is that (since this was a exploratory study) we had severely limited funds and so were not able to build and test a complete prototype. However, we did manage to evaluate key components by using test-circuits to verify their operation, and we are confident that these provide accurate enough results for the purposes of this study.

7.2 System Overview

The system is grouped into units called modules, which in turn are composed of a collection of mini-modules combined with bespoke hardware. Some of the modules provide supervisory or general services, whereas others are dedicated experiment support modules. We discuss each module in a subsequent section of this thesis, but there are several topics common to the various modules which we will discuss here first.

7.2.1 The Small Single Board Computer

The SSBC is a computer comprised of, at bare minimum, a processor, associated memory, permanent storage and an operating system, all contained on a single PCB. The SSBC must be a drop-in replacement, allowing it to be upgraded to accommodate increasing operating system requirements as well as to adapt to future network protocol changes, or simply to allow easy replacement of broken or damaged units.

Since the SSBC runs the connection interface to the module, it must be able to communicate with the modules hardware to get measurements as well as give instructions. We chose the USB standard to communicate between the boards, as it allows very high speed data transmission and also enables the motherboard to be plugged directly into a computer for debugging purposes during development.

Currently the system uses a second generation USB interface, capable of 480 Mbps. [Intel et al., 2000] This is enough bandwidth to transfer even high-frequency measurements. However, some modules may require very high transfer rates and will have to be upgraded to USB 3.0 and 3.1 that have a theoretical bus capacity of 5 Gbps and 10 Gbps respectively. [Hewlett Packard et al., 2013]

For our specific implementation we are using the "Raspberry Pi 1 Module B+". [Raspberry Pi Foundation, 2015]

7.2.2 The Enclosures

In keeping with the design from the second prototype, we will be using 19 inch computer sub-rack enclosures. This allows each module to be scaled according to the requirements of the hardware (by selecting a sub-rack of a different height) as well as ensuring that modules are developed years apart will be able to fit into a new standardised laboratory workbench designed for this equipment system.

7.2.3 Mini-Modules

The aim with mini-modules is to allow developers to benefit from the work being done by other research teams by combining shared functions into drop-in replacements. There are two key advantages to this, namely that developers will be able to get new systems up and running quicker by limiting time spent on redesigning components, and that they will be able to upgrade existing equipment if new units become available.

The challenge comes in defining the interface, since ideally the unit must only have a data connection and a physical link to the circuit being measured. We attempted to design a watt-meter mini-module with a generic interface that could be adapted as required, but it soon became apparent that this is simply impractical. The biggest challenge is the socket, which becomes unnecessarily expensive just to accommodate possible future expansion.

Instead we propose providing the mini-modules to other developers as a circuit snippet, or small design part that can then be integrated into the specific format required by each developer. These elements can also be made available in the formats of popular circuit layout tools.

7.3 Module: The AC Power Supply

7.3.1 Overview

The AC power supply module takes a single power connection from the network and distributes it to all the other modules in a safe and controlled fashion. (The module is shown in Figure 7.2.) A system for practical education could have a number of modules, so our first concern was safe and reliable power distribution. We wanted the student to be able to safely connect and disconnect the components. But, we also wanted to protect the equipment, as well as the power supply.

Figure 7.2: Perspective view of the AC power supply module from the third prototype. *(Rendering by Author)*

Each module is provided with a power connection at grid level and must convert this into the various power levels required. This increases the flexibility of the modules as they do not require special power supplies. Thus the AC power supply only distributes the power and does not convert it.

On the AC power supply, power enters through a 16 A International Electrotechnical Commission (IEC) connector. Some of the power is split off to a AC-DC converter to power the on-board electronics of the module itself. The majority of the power connection is split into seven power output ports that can be used by modules in the system.

Each output connection is rated at 230 V_{AC}, 50 Hz and 2 A. The on-board microcomputer reads the wattages from the set of watt meters, ensuring that the power levels are not exceeded on any power port. This information can be requested through the module's data interface. Since power can be measured on an individual output channel level, the master controller can provide the AC module with custom trip levels for each channel depending on the connected equipment.

The input can also be measured, allowing the system to compare the total and combined power usage constantly, ensuring that problems inside the AC power supply module are also detected early.

The input is fed directly into an AC-DC converter, which allows the on-board controller to come online first. The input AC power is then fed through a set of normally open relays (on both the live and neutral lines), is split, and then each channel is fed through a separate output relay on the live phase. When a user initiates the system, the controller will start by opening the master relays, and it will then provide power to the specific channel containing the main computer. When the main computer has been powered on, the system will energise the other ports. Unused ports are kept isolated, ensuring user protection.

The wattmeter consists of an ammeter and a voltmeter, both of which were designed as mini-modules.

7.3.2 Operation

The top-level schematic layout is shown in Figure 7.3. (For a complete set of schematic drawings, please refer to §C.1.)

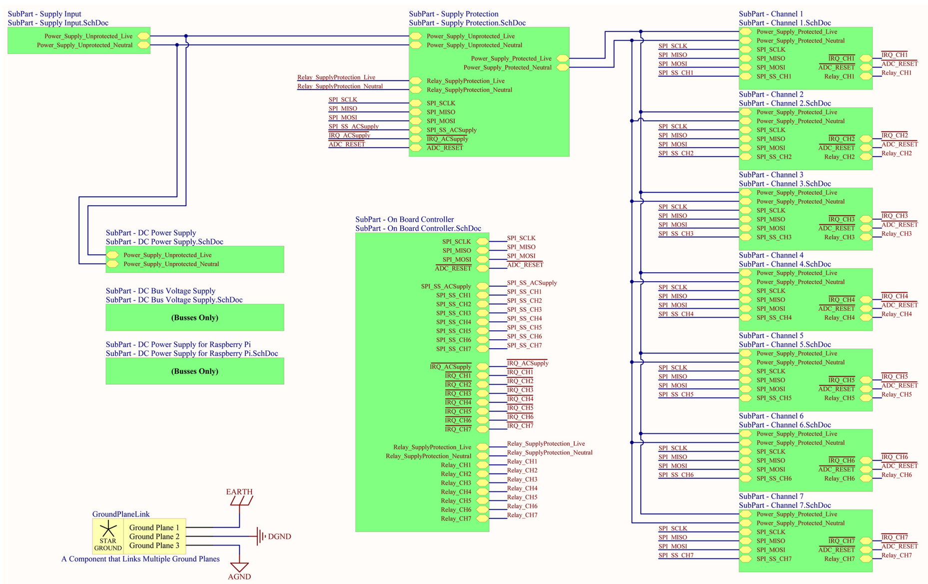


Figure 7.3: Top-level schematic for the AC power supply module from prototype three.

We start where the AC grid-connected power enters the module through the *Supply Input* on the left, discussed below in §7.3.3. (The schematic design was done in such a way that power flows from left to right.)

Next the power moves through to the *Supply Protection*, where it is measured and isolated from the output circuitry. Some of the power is first split off and feeds the AC to DC converter which in turn feeds a set of linear regulators that create the supply voltages, discussed in §7.3.5. These power the on-board computer, enabling communication with the module, as well as providing a valuable protection feature.

The *supply protection*, discussed in §7.3.4, will only energise the output section when the user confirms a start on the front of the module, ensuring that the equipment only powers on when intended. We discuss the on-board computer and its AC to DC converter in §7.3.6.

The power flows out of the module through one of the seven *output channels*. Each output channel performs a power measurement and also isolates the channel from the outside with a relay. The relays in the output channels, as well as in the input channel, are connected on normally open relays, which means that any loss of control will immediately open the relays. (The PCB can be seen in Figure 7.4.)

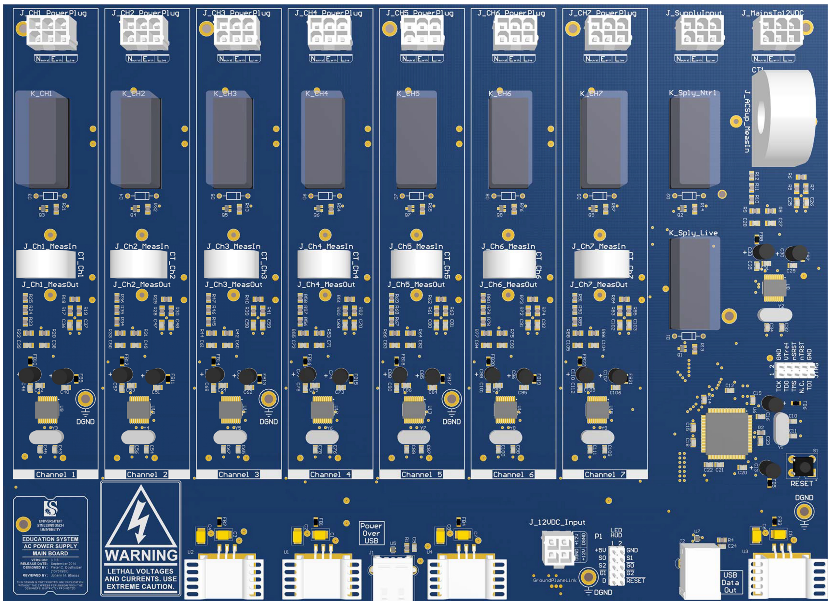


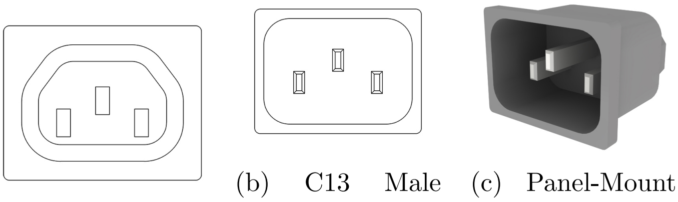
Figure 7.4: Top view of the AC power supply module PCB from prototype three. *(Rendering by Author)*

7.3.3 Design and Development of the Supply Input Section

The supply input is where the external power cable connector links into the circuit board. We wanted all modules in the series to use a standard power connector and, as far as possible, to avoid situations where custom links have to be constructed, preferring off-the-shelf components.

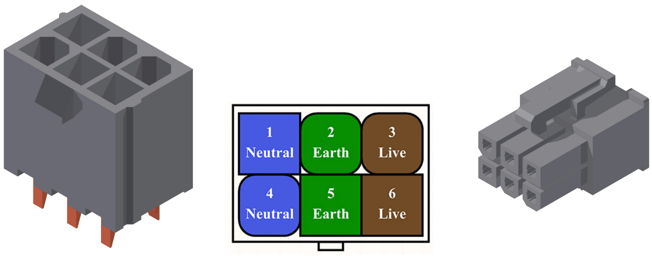
We chose to use IEC60 320-1 C13 and C14 power connectors, pictured in Figure 7.5. The passive connector side is exposed, while the active connector side is enclosed, excluding accidental contact. The ground pin is also longer, ensuring that it is always connected first and disconnected last. In South Africa they are rated to carry 16 A at 230 V, 50 Hz AC. Three wires extend from the connector to the PCB.

To connect the wires to the board we use a Series 5566 3x2 wire-to-board connector from Molex, shown in Figure 7.6a. The connector has six pins, allowing



(a) C13 Female (b) C13 Male Connector (c) Panel-Mount Version

Figure 7.5: The IEC60 connectors proposed for use in all modules of prototype three.



(a) Series 5566 3x2 Connector (b) Board Side Pin-Out (c) Series 5557 3x2 Connector

Figure 7.6: Molex connectors proposed for use as power-to-board links for external components in all modules of prototype three.

for the allocation of two pins each to the live, neutral and earth phases respectively. Since each pin is rated at 13 A we get 26 A maximum current capacity per phase as shown in Figure 7.6b. The wires are fitted with a series 5557 plug, shown in Figure 7.6c, making it easy to unplug in case the PCB needs to be removed.

7.3.4 Design and Development of the Supply Protection Section

The supply protection has two important sub-sections, namely the relay to control the flow of energy, and the wattmeter to measure it. An overview of the design is shown in Figure 7.7.

The relay section is similar to the ones used in the output channels, and the wattmeter is also shared.

The relays are chosen to handle the current in a 230 V_{AC} system. One of the major reasons for staying with AC up to the final module, is to allow us to do the protection on the AC side, since this brings down the currents, allowing us to use cheaper relays.

The Relays

The relay circuit is presented in Figure 7.8. The component is a Relé Series E relay. We chose this series as it provides the electrical characteristics required, is

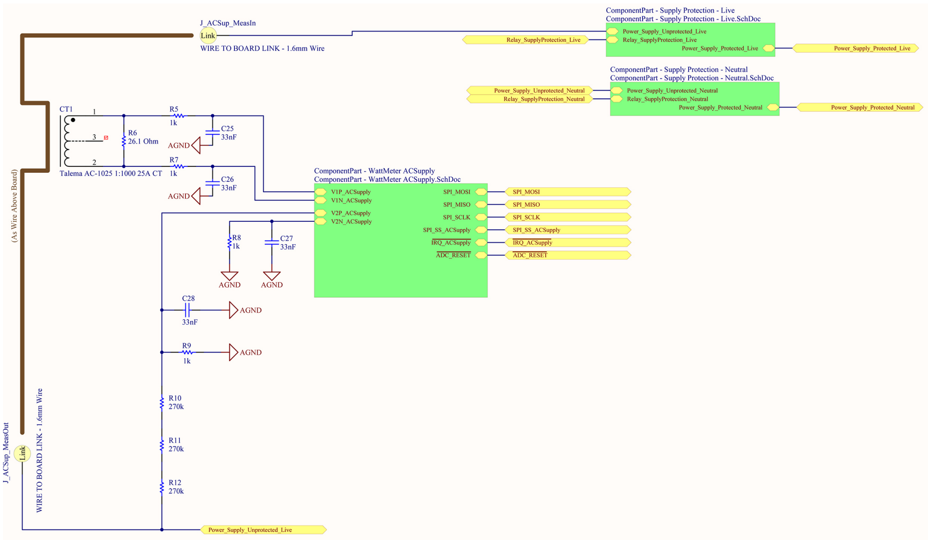


Figure 7.7: Overview of the supply protection section of the AC power supply module of prototype three.

cheap and readily available, and has a range of relays that have a similar footprint for different levels of current. The E61/S, the specific model used in the supply protection circuit, is a single pole, dual-throw model with a 12 V_{DC} coil.[Italiana Relè, 2011]

For the protection of both the system and the user the relay will also connect the outgoing side to ground in the event of a power or communication failure. This ensures that the wires are never accidentally live. The relays are connected to the on-board computer through an N-Channel Metal–Oxide–Semiconductor Field-Effect Transistor (MOSFET) transistor, allowing it to directly energise the relay without additional drivers.

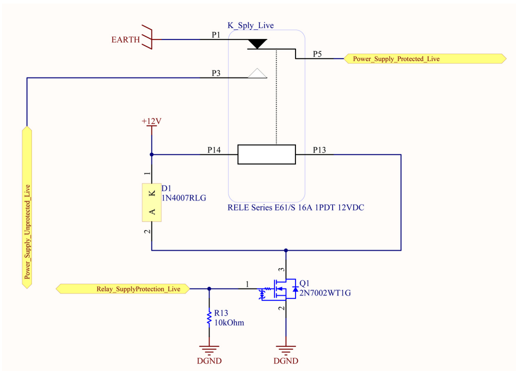


Figure 7.8: Relay protection circuit of the AC power supply.

The Wattmeter

The wattmeter detail circuit is presented in Figure 7.9. The core of this device is the Analog Devices ADE7763 which is a single-phase active and apparent energy measuring integrated circuit.[Analog Devices, 2013] The wattmeter went through several design iterations, and it is important to discuss this here in some detail. The major problem arose from the desire to have a single watt-meter module that would be able to fit everywhere inside the system as a mini-module. This approach, however, presents a few problems.

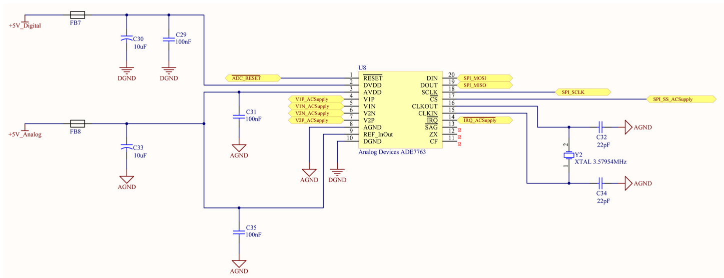


Figure 7.9: Wattmeter circuitry of the AC power supply.

There are a number of AC and DC signals in the system. Since we experiment on solar systems, we realised that we needed to measure high levels of DC voltages and currents. However, we also had to measure small DC voltages accurately, such as the 12 V_{DC} power buses on the system where accurate small-scale measurements are required. Measuring this with a single volt meter design would require a high-resolution analogue to digital converter, making the system unnecessarily costly.

The same is true for the current measurements. But here it is further complicated by the difference between measuring current in AC and in DC systems. In AC systems we can accurately measure the current using a Current Transformer (CT). However, in DC systems we need to use a shunt-resistor. To ensure that the measurement equipment does not affect the measurement itself it is important to keep the shunt resistor as small as possible, which is difficult if one has to design simultaneously for small and large currents.

In both cases there are designs that can be suggested to solve the problem, but they are costly and complex, making the equipment expensive to buy and difficult to maintain. In the end we opted for some shared elements, and a common interface to the processor.

Since the supply voltage is the South African grid voltage, we can design the wattmeter to handle the full capacity of 230 V_{AC} at 16 A.[Standards South Africa, 2007] This is the type of circuit that can now be included in all the modules that requires power measurement of grid-level power.

On the board itself we use a Talema AC-1025 1:1000 25 A current transformer. [Talema, 2004] (On the output channels we used the Murata 56050C 1:50 10 A model.[Murata Power Solutions, 2008]) On the PCB a connection allows one to solder a 1.6 mm diameter wire to the board, as shown in Figure 7.10. The wire is connected to the *J_ACSup_MeasOut*, moves through the CT, and is soldered back into *J_ACSup_MeasOut*.[1]

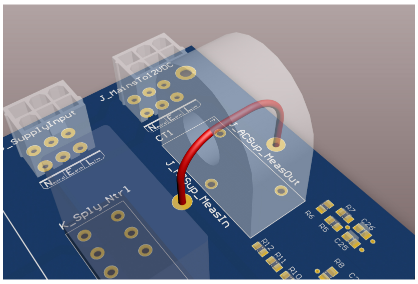


Figure 7.10: Demonstrating the wire loop through technique to allow the use of current transformer in the AC power supply module.

Three resistors, two in series and one parallel across the CT, sets the measurement value depending on the ratio of the current transformer. Small decoupling capacitors to the ground plane clean any transient noise on the system. The voltmeter uses a voltage divided resistive circuit to provide the required voltage rail levels. The chip itself requires both an analogue and a digital voltage rail, at +5 V_{DC}. The chip connects to the on-board integrated circuit through the SPI standard. A reset line is also connected to allow the device to be reset by the on-board computer, as well as to disable it.

A last note, on the use of ferrite beads on all the DC supply lines: this cleans up any high-frequency noise that may find its way onto the power transmission lines.

7.3.5 Design and Development of the DC Power Supplies and Bus Levels

Four DC voltage levels are needed:

- **+12 V_{DC}** to power the relays,
- **+5 V_{DC}** supply on a separate ground to power the digital electronics,
- **+5 V_{DC}** supply on a separate ground to power the analogue electronics, and
- **+3.3 V_{DC}** supply on a separate ground to power the micro controllers.

[1] We tried to use clear identifiers on the PCBs to allow developers easy reading of the PCB during installation and debug.

Since the AC-to-DC converter is the most expensive component, we decided first to convert to $12\mathrm{V_{DC}}$ and then to use linear regulators to step down to the voltages we need after that, especially since the lower voltages require very little power. The power budget was performed and can be seen in Table 7.1.

Table 7.1: Power budget for AC power supply module of prototype three.

Sub System	**Voltage Level (V)**	**Max Power Use (W)**
Main Controller	3.3	0.066
Power Over USB	5	4.5
LED Indicators	5	3.024
Protection: Live	12	0.6
Protection: Neutral	12	0.6
Protection: Watt Meter	5	0.035
Channel: Protection	12	4.2
Channel: Watt Meter	5	0.245
Total		13.27

Each sub-system in the power budget is listed along with the total energy required at the specific voltage level. The designated power usage for the Power Over USB system, which powers the SSBC (in this case a Raspberry Pi), has been set at the maximum allowable power permitted by the USB 2 standard, augmented by the Universal Serial Bus 2.0 Power Delivery Specification.[Intel et al., 2000] [Apple et al., 2014]

We selected the Traco Power TXM 025-112 AC-to-DC converter. It is a 25 W module, resulting in a design safety factor of 1.8. The unit delivers 2.1 A at 12 $\mathrm{V_{DC}}$ with an 82% efficiency.[Traco Power, 2012] The output voltage is adjustable, allowing accurate calibration, but this is not very critical as the relays' sensitivity is more than the output variation of the power source.

To step down from the 12 $\mathrm{V_{DC}}$ to the other required buses we used the Texas Instruments LM1086 series of low dropout positive regulators, specifically the *LM1086-3.3* and the *LM1086-5.0*. These regulators are able to deliver the output voltages of 3.3 $\mathrm{V_{DC}}$ and 5 $\mathrm{V_{DC}}$ respectively from an input voltage of between 6.5 $\mathrm{V_{DC}}$ and $18\mathrm{V_{DC}}$, well within the limits of the AC-to-DC power supply variation.[Texas Instruments, 2005] These units have a line regulation of between 1.0 mV and 10 mV, which is within acceptable bounds for the electronics it will power.

Since we are using the units simply as voltage regulators we connect them to the power source, and decouple using shunt connected 10 μF tantalum capacitors, as recommended by the data sheet. We also separate the grounds, by setting two of the buses (one 5 V and the 3.3 V) on a shared digital ground, and the other 5 V on a separate analogue ground. All the grounds are connected together, including the earth, at only one place on the board, ensuring that various components do not accidentally broadcast noise between buses.

However, although the linear regulators are capable of supplying the required power, the resulting current levels will results in a large dissipation of power within the regulator itself. It is advisable to rather introduce a second AC-to-DC converter to directly create a 5 V_{DC} bus from the 3.3 V_{DC} buses can be sourced.

Power-Over-USB

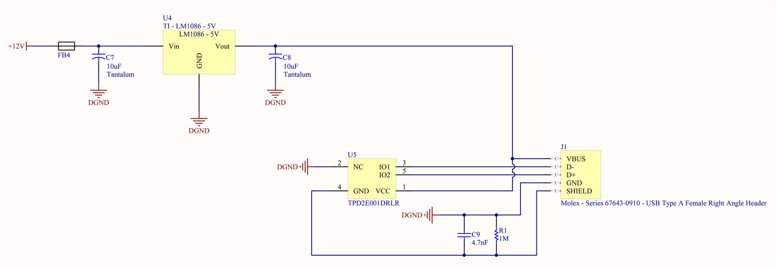


Figure 7.11: Power-over-USB circuitry from the AC power supply in prototype three.

The power-over-USB circuit, shown in Figure 7.11, has its own 5 V regulator, sharing the digital ground, as well as an ESD-protection circuit specifically designed for high-speed data interfaces.[Texas Instruments, 2008] Since the USB connection is a potential point of damage it was decided to protect it against any Electrostatic Discharge (ESD) strikes. However, the circuitry on the PCB cannot be protected against somebody touching the electronics directly, so a reasonable amount of care on the part of the installer is still expected.

7.3.6 Design and Development of the On-Board Computer and its Support Systems

The module's motherboard uses an 8-bit microprocessor. This is responsible for all the functions on the board itself, including processing all front-panel user input as well as providing feedback using the LEDs.

When choosing the processor we considered the following:

Availability: South Africa has a more limited availability of processors than the United States and most of Europe. We chose devices which are currently in high use, thus stocked by most of the distributors.

Affordability: The processor must provide the required functionality at the least cost. This cost, however, includes the programming interfaces, development time as well as installation complexity.

Technology Familiarity: Constant developments in microprocessor technology result in a wide variety of companies with exceptional products, making it appealing to change to the latest technology to gain its advantages. But, what is often neglected is the importance of developing a knowledge base within a laboratory and department. Developing a set of tools, libraries and a general working knowledge of a specific company's technology cannot be ignored. This also makes the processor decision very difficult, as the company must not only have a good solution for the current project, but a wide variety of products.

Engine: We only considered the 8-bit microprocessors. Since the external SSBC will be doing the heavy-lifting, the on-board computer must prioritise general IO and low-lever interfacing.

Input/Output Ports: A number of items will need to be controlled, or values be read. There must be enough space for this on the processor.

Serial Peripheral Interface: We have used SPI on our designs, and the processor must support this. Since SPI uses a chip-select line the processor must also have enough outputs for each of the control lines.

USB: The processor must support on-chip USB interfacing.

Analogue to Digital Conversion: Even though we will use external ICs for the detailed capturing, it is important to have a couple of ADC channels available for small measurements.

Temperature Sensor: Since the equipment will be working in a variety of environments it is useful, but not required, to have a temperature sensor.

We evaluated the following technologies, the AVR®MCUs from Atmel, the PIC®MCUs from Microchip®, the RL78, 78K and the R8C MCUs from Renesas, and finally the MSP and Hercules Microcontroller (MCU) ranges from Texas Instruments.

This was a difficult evaluation as one has to weigh not only the current offering, but the roadmap provided by the company for future development. Design support, availability and various other factors had to be considered, as well as the knowledge and skills currently available in the department.

For our needs the Atmel processors were the best choice. So, for the on-board computer we chose the Atmel ATxmega128A1U microprocessor, which is an 8/16-bit high-performance microcomputer based the low powered Atmel® AVR® XMEGA® range.[Atmel Corporation, 2014]

The following sections detail the implementation of the MCU into the design.

Overview of the Integration

The processor is supplied in a 100-pin Thin Quad Flat Pack (TQFP) package. The flat layout and small size of the processor require careful consideration from the designer when choosing which of the output buses to put specific connections on as it is easier to change the location of the port in software than it might be to do the physical layout. An example of the routing is shown in Figure 7.12 to demonstrate this.

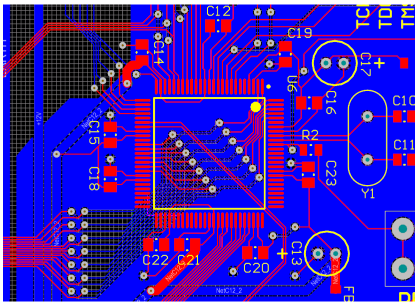


Figure 7.12: Routing required to connect the MCU

Power Requirements

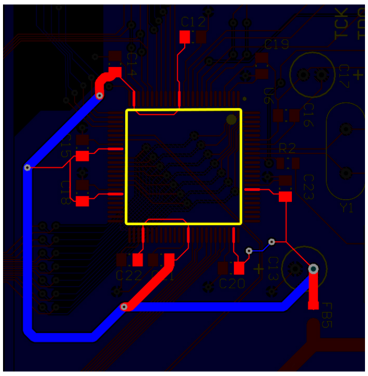
The processor has multiple power and ground connections, and has been designed according to the guidelines provided by Atmel.[Atmel Corporation, 2010]

The processor is powered from the 3.3 V_{DC} bus. We used a series of capacitors and ferrite beads to ensure the correct operation of the power supply for the processor. The ideal would have been to route the power underneath the chip, but because one needs the ferrite beads and capacitors and, with the lines not fitting between the processor pins, it is simply not possible. This results in the power having to run around the entire processor, making it difficult to route all the IO pins. Figure 7.13a shows the power structure highlighted, ground excluded, and Figure 7.13b shows the space used by this power structure on the PCB.

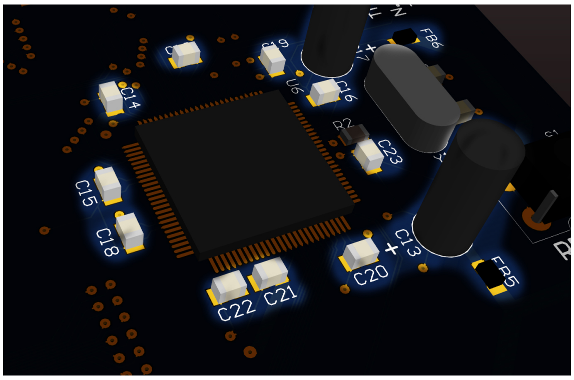
To supply the analogue connections we used the same 3.3 V_{DC} supply, with the digital ground. But we placed an additional ferrite bead into this line to promote the separation of noise-influencing components.

USB Connection

To connect the PCB system we used the same ESD protection chip from Texas Instruments as before. The physical connector is a Molex Series 67068-8010 PCB Type B jack.



(a) MCU power structure routing.



(b) MCU power structure PCB.

Figure 7.13: The MCU power structure of the AC power supply in prototype three.

JTAG Programming Interface

We used the Joint Test Action Group (JTAG) programming interface which allowed us to programme and debug the chip inside the circuit. This is a great advantage of this technology, and significantly reduces development time. The connection is a simple 5x2 header that is connected to the processor. Since we did not share the JTAG line with other communication buses, it simplifies the design as we did not need to compensate for the possibility that the programmer will start powering other devices during programming and operation.

7.3.7 Design and Development of the Front Panel for the AC Power Supply Module

The LED front panel is pictured in Figure 7.14. The front panel provides basic feedback to the users, helping them to identify problems faster. We wanted a technician or the student to be able to figure out what is wrong with a unit without having to connect a computer or use other complicated diagnostic tools.

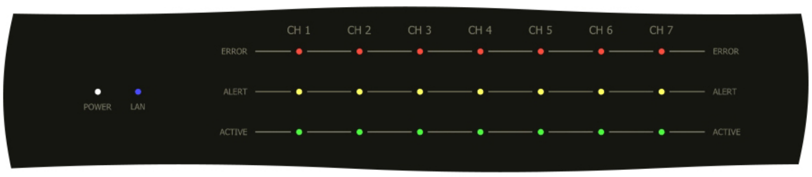


Figure 7.14: Detailed view of the front LED status panel of the AC power supply from prototype three. *(Rendering by Author)*

The information critical to this module is the status of the module's power supply, the on-board computer, the Local Area Network (LAN) connection, as well as the status of the seven power output channels. (The PCB is shown in Figure 7.15.)

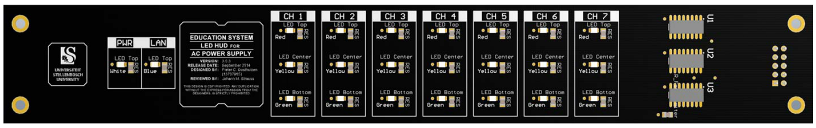


Figure 7.15: PCB of the front LED status display PCB from the AC power supply of prototype three. *(Rendering by Author)*

The module is read from left to right, top to bottom. This design affordance increases the unit's understandability.

Power Indicator: The first indicator, the module power, uses a white LED, showing that the unit has power. When a user switches on the first (red) power switch the power-led will start flashing — indicating that the module is powered but that the system and the computer is not yet ready. Once the system is ready and stable, the power-led will burn continuously.

LAN Indicator: Once the module has been powered up, the LAN indicator will start to flash. This indicates that it is trying to connect to the local network. Once a network connection has been established, the light will burn continuously. (If the network is the custom internal network, then the LAN will only be available after the user has opted to energise the output ports.)

Channel Indicators: Once the user enables the green switch, the system will start to energise the output channels according to the recorded values for what is to be powered by each of the channels. In the event that no equipment is registered, or where the system starts to detect faults, it will simply flash the 'error' lights. Alternatively if the channel energises correctly the 'active'light will flash and then burn continuously to indicate the channel is active. Any problems will be indicated by the 'alert' light.

The LED module uses three latches, with built-in demultiplexers, to drive the lights. (The detailed circuit diagrams are attached in §C.2.) The processor connects directly to the module, and drives the input pins directly. Even though the processor only produces 3.3 V on its output, the input to the latches will still register this as an active high.[Texas Instruments, 2003]

The LEDs are all from the Osram Mini TOPLED range. This range was chosen for its variety, as well as the high power efficiency. [Osram, 2008a, Osram, 2008b, Osram, 2008c, Osram, 2008d]

7.3.8 Recommendations

The module provides a clear starting point for the user when operating the system. Even though the modules do not require a single power supply, the starter and general safety mechanisms make it not only valuable for use in the practical laboratory, but also for postgraduate research work. Furthermore the module's ability to record the total power used by the system makes it an ideal inclusion in remote measurement research stations, as it will be able to keep accurate track of the equipment as well as the power used by the system itself.

However, there are a few elements we feel need improvement. Indicators that flash for different states require the user to have to read a manual to check the error. Rather include two more status lights, one to indicate that the computer is working and the other to indicate that the on-board computer is ready, separating it from the power light.

The unit also requires an emergency stop button. An emergency button, with twist release, must be added on the front, but a connector must also be added to the back of the module to allow an external emergency switch to be connected which can be placed on a work bench, or near a security screen for remote operations. The current green button also needs to change to a push button to indicate the start-stop nature of the button.

Furthermore, it would be ideal if the power module could also house the alarms, bells, lights and other systems to warn users when the system is being used in the remote mode and is about to power on. The emergency buttons would then allow users nearby to suspend the system.

Alternatively, developing a dedicated module to handle a remote operation safety is more in keeping with the design principles of this system. This would also allow such a unit to include more advanced safety features, such as safety beams, interlocks, and so forth.

7.4 Module: The Practical System Controller

The practical system controller (shown in Figure 7.16) is the module that runs the practical laboratory software package, to be discussed in more detail in §8.4. The module also connects to the touch screen as well as any other physical user-interfaces, and provides the user with a slot for the storage and retrieval of information from USB flash-memory cards.

Though we initially thought of using a SSBC for this purpose, the units are simply not powerful enough to run all the services we need, specifically for rendering the graphics in high-resolution to the screen while providing network access and enough powered USB ports. We could add more USB ports, even split the load onto multiple SSBCs, but we wanted to simplify development.

Figure 7.16: Perspective view of the practical system controller module from the third prototype. *(Rendering by Author)*

To this end we decided on a regular desktop computer, but installed inside a sub-rack case. This allows developers easy upgrading and maintenance of the unit, as well as ensuring that it is compatible with the Linux operating system.

The only limitation is that the module cannot use more than 400 W of power — which is possible if the machine does not include a graphics card or a high-end central processing unit, neither of which is required for our application.

7.5 Module: The Network Link

The purpose of the network interface module (shown in Figure 7.17) is two-fold, namely to connect the various modules to each other on a private network, and to connect that network to the general Intranet or Internet.

Universities vary significantly in the way that devices can connect to their networks. The differences range from how the new equipment is assigned an IP address (our university for example assigns fixed IP addressed to all new equipment based on their registered MAC addresses) to how the devices connect to the internet or where on the network the equipment is visible. Sometimes there are software authenticators that must be installed, requiring a user name and password before allowing access to the network. All this prompted us to install a dedicated computer to run just the network link and firewall.

Furthermore, the systems includes a variety of modules, each taking up an IP address. For example, if we converted our department's machine laboratory (with its 20 workbenches) to the proposed practical system, assuming that we used a slightly larger model with six modules, we would occupy 120 IP addresses. Given that the largest network switches are 48 port units, our setup would require the university to install three switches dedicated only to this practical system. This

Figure 7.17: Perspective view of the network link module from the third prototype. *(Rendering by Author)*

is unsuitable. Using an intermediary network interface brings this down to 20 IP addresses.

There are other problems too. If every module is directly connected to the university Intranet, then each module requires its own firewall and security settings.

The network link module provides a private network to solve this. But, developing a switch is complicated and unnecessary. A simple solution is to use an existing switch and to build it into a sub-rack, extending the connectors to the back and the indicator lights to the front. Inside the sub-rack we also install a SSBC to connect to the Intranet.

7.6 Module: Solar PV Dummy Load

7.6.1 Overview

The solar photovoltaic dummy load (pictured in Figure 7.18) is an experiment support module. (See §C.3 for a complete circuit diagram.) The dummy load is used to allow students to conduct experiments in solar photovoltaic systems. It provides the user with several connections for solar panels on the front, using standard solar connectors. There are two inputs, for the two panels, and internal logic allows the user to connect these panels in series, in parallel or to select only the first panel on its own. (The populated PCB is shown in Figure 7.19.)

The input is fed through a wattmeter, providing voltage, current and power output. It is then fed into the dummy-load itself, which is able to dynamically vary the load seen by the solar panels, allowing the student to evaluate the solar panel under an array of conditions.

There were two design options for the dummy load. The first is a digital

Figure 7.18: Perspective view of the solar PV dummy load module from the third prototype. *(Rendering by Author)*

variable resistor, which uses a buck-boost converter design to change the duty-cycle across a 1 Ω, high power resistor. As the duty cycle changes, the value of the resistor as "seen"by the solar panel will change.

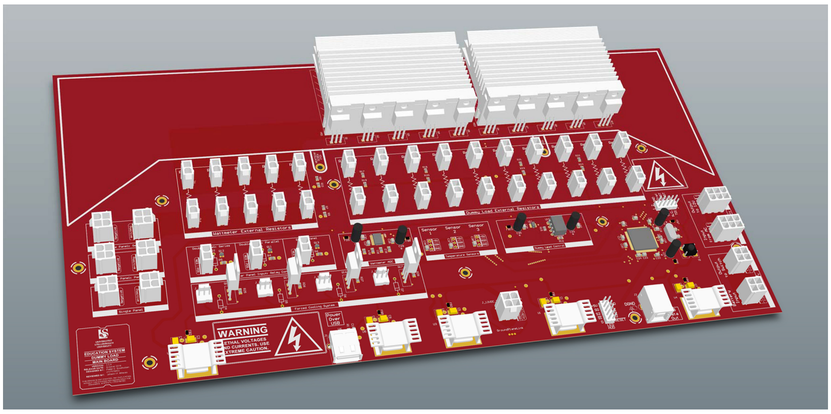


Figure 7.19: Perspective view of the solar PV dummy load PCB from the third prototype. *(Rendering by Author)*

The second option is a transistor-resistor circuit. This system uses a set of high powered MOSFET transistors operating in their triode region (also called the ohmic or linear region) where they exhibit a linear relationship between current and voltage, which to the solar panel makes them appear like a resistor.

We did both designs, but chose the transistor-resistor solution since it is a simpler circuit to construct, has a better load curve, is less sensitive to component tolerances and is able to provide a much better short-circuit condition.

7.6.2 Design and Development of the MOSFET Linear Region Digital Variable Resistor

The digital variable resistor works by operating an N-channel MOSFET in its triode region. (A simplified version of the circuit is presented in Figure 7.20.) Most of the power is dissipated inside the transistor, which can make the circuit costly as high-powered transistors are expensive. However, driving multiple transistor circuits in parallel allows the power dissipation to be distributed across these lower-cost unit. (Shown in Figure 7.21.) This distribution also simplifies the heatsink design and efficacy, as the generated heat is not localised to a single point but can be spaced out to cover a larger surface area.

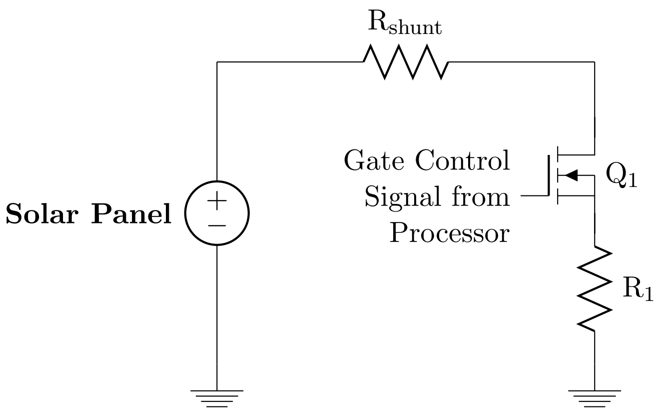


Figure 7.20: Basic circuit demonstrating the operation principle of the variable resistor of prototype three.

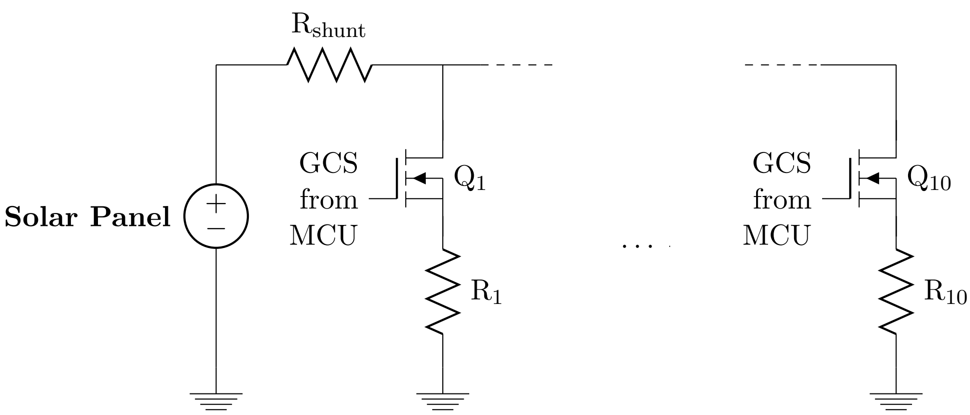


Figure 7.21: Expanded circuit demonstrating the multi-transistor setup used to distribute heat dissipation in the variable resistor of prototype three.

We chose the *IRFB3306PBF* from International Rectifier. This is a 60 V, 120 A N-channel MOSFET in a Transistor Outline Type 220 (TO-220) case, specifically a TO-220AB. We paired this with a Fisher Elektronik *SK 487/84*

SA heatsink, since the unit mates with TO-220 cases, providing a lower thermal resistance. (The transistors and heatsink are shown in Figure 7.22.) The heatsinks and transistors are enclosed in the heat pipe during installation.

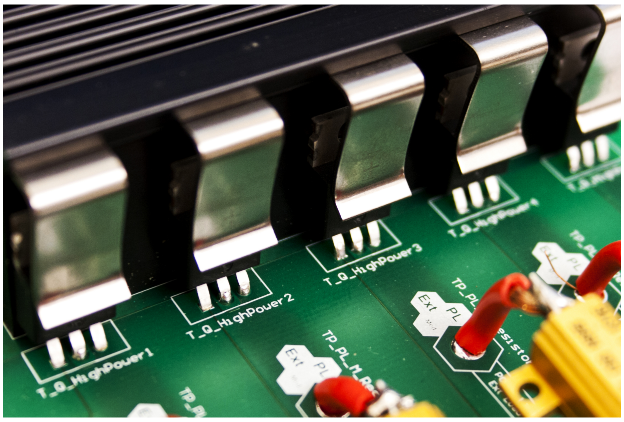


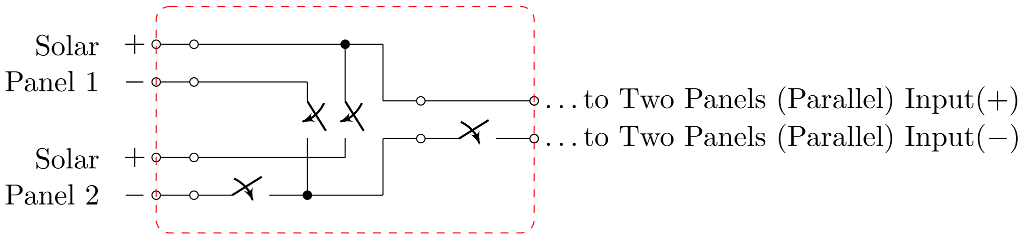
Figure 7.22: The installed heatsinks and transistors of prototype three. *(Rendering by Author)*

The accuracy of the transistor circuit is largely dependent on the gate control signal applied. The processor only has a 12-bit Digital to Analogue Converter (DAC), so we chose to add a dedicated *AD5662* 24-bit DAC from Analog Devices. [Atmel Corporation, 2014] [Analog Devices, 2005] The transistors do not turn on before 3.4 V, so we need a full range output from the DAC of between 2 V and 9 V. We use a non-inverting amplifier to lift the ground as well as scale the output values. The 24-bit DAC has 16,777,216 possible values, giving an effective step value of 417 nV.

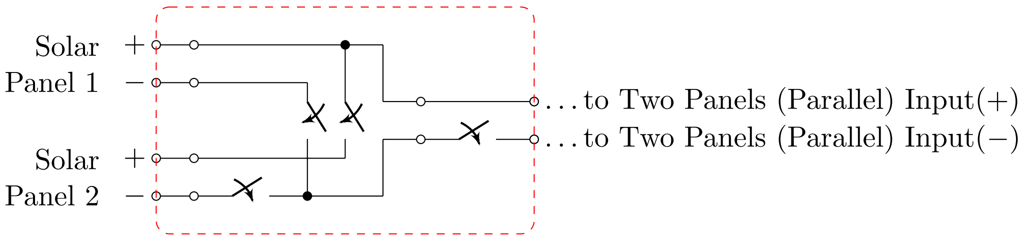
7.6.3 Design of the Solar Panel Input Section

The solar panel input has been simplified from the one proposed in the second prototype. The dummy load module has two connectors on the front of the unit for the two solar panels. Inside the module there are three circuits, which allow the user to choose to connect the dummy load only to the first solar panel, shown in Figure 7.23a; both panels in series as shown in Figure 7.23b; or both panels in parallel as shown in Figure 7.23c. Each of these connection circuits can be connected to the input terminals on the PCB using a selection of relays. Once a specific configuration has been selected, the relays of that specific circuit are closed.

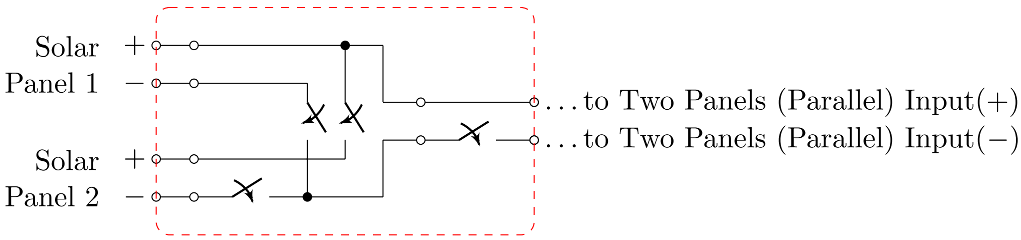
For this prototype we use solid state relays from the 22 Series by Finder.[Finder S.p.A., 2015] Because the units are very big they cannot be housed on the circuit-board itself — they are installed inside the casing, and connected to the PCB using Molex power connectors for both the incoming solar panel power as well as for the relay's coil energising power.



(a) C13 Female



(b) C13 Male Connector



(c) Panel-Mount Version

Figure 7.23: The three input configuration selection circuits of the dummy load module from prototype three.

The circuitry connecting the relays to the front connectors are all done using direct wires rather than a separate circuit board. The advantage of this installation arrangement is that if this component breaks, which is likely as it is the position in the circuit that will break the most current, the component can easily be replaced.

However, to ensure that the component does not fail unnecessarily fast, the system will be given two stop modes. These modes are available to the student, and provide different ways to disconnect the panels from the circuit. The first is the normal safe stop, where the dummy load resistor will ramp up, providing a very high initial resistance to the solar panels, forcing them into open-circuit mode and reducing the current flowing through the circuit. This can happen very quickly, but is not a safe way to do it in case of an emergency.

The second shut-down mode provides the student with an emergency switch that uses the relays to disconnect the solar panels, forcing them to break the current. This mode will also be used by the computer in all abnormal situations, such as an over-temperature warning on the cooling system, to ensure that the energy is disconnected as soon as possible.

7.6.4 Design of the Heat-Pipe

The system will generate a lot of heat. In maximum mode it will be dissipating 725W of energy. To get this out of the system as fast as possible, and to avoid unnecessary contact of this heated air with other components, which could introduce noise as well as non-ideal behaviour, even component failure, the heat-sinks are installed inside a steel heat-pipe, with four fans forcing air inside the system and pulling out hot air into the atmosphere at the other end.

The system was designed to have an enlarged opening and exit, forcing air into the smaller channel, accelerating it and increasing the turbulence on the heat sink blades. The fans are installed inside the intake and exhaust side of the duct. A set of temperature sensors measures the incoming and exhaust air, to determine if cooling is possible, and if it is working. Fan speed is also measured to ensure that the fans are performing as expected.

The heat-pipe, as installed with fans, is shown in Figure 7.24.

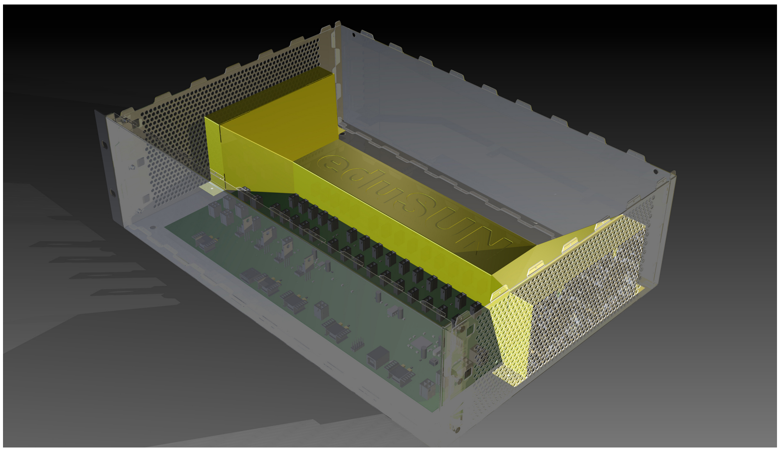


Figure 7.24: The heat-pipe from prototype three installed inside the case, highlighted in yellow. *(Rendering by Author)*

Since the fans move air from one side of the case to the other, it is vital that the system is not installed where the fans are blocked or covered. The reason why it blows out of the sides and not the back is twofold: firstly we wanted to ensure that the air can move from one side to the other, rather than having to move in and out at the same side. Secondly we wanted to design the system so that it never blows air out of the back where the wires and connections are, since the hot air would heat the wires and lower their current rating.

7.6.5 Recommendations

The dummy load module can be used during practicals as well as for research experimental purposes. However, we found that this duality presents a few problems with the design choices that have to be made during development, including the required accuracy of the measurement circuits, or the design of the enclosure. A researcher might require very accurate measurements as well as a waterproof enclosure for field testing.

But this is incorporated into the proposed development path. Even though researchers might rebuild the electronics into a different case, they will still be developing a working dummy load system that is then shared with the community. And given that the measurement circuit is a mini-module, it can simply be replaced with a less accurate and cheaper unit for the practical system.

7.7 Chapter Summary

In this chapter we discussed the development of the third prototype's hardware components. The major difference between this system and the ones presented in the first and second prototypes is that this system cannot realistically be carried outside as a whole. However, because of the network based operation, this is not necessary. The control module, along with the network and AC power modules could be installed in the laboratory and then connected to a remote unit on the laboratory's roof. For our specific practical application it would also be ideal to add additional experiment specific modules, such as a weather station module, a heliostat control module and a camera module to monitor the external setup in real time.

More research will be required to determine the best collection of modules for starting a new development, as well as which design elements to include in the framework. Ideally the developed system must serve more than just a single university or group. As such it is imperative that developers also focus on documenting and publishing their developments to the broader academic community.

However, the lack of a complete prototype is detrimental to the research, and will have to be addressed before any future studies can be made. A physical prototype will allow for user testing, as well as a much more detailed analysis of the electronic design challenges beyond the elements introduces in this thesis.

Chapter 8

Third Prototype: Software Front-End

8.1 Introduction

There are several software layers on the practical engineering education system. In this chapter we are concerned with the two uppermost layers, namely the *Practical Laboratory Software Package* as well as the *Data Interface Service (DIS)*, both of them running on each module. The development of the system is beyond the scope of this thesis, but our aim in this chapter (similar to that of Chapter 6) is to investigate the requirements and possible challenges of developing such a system.

First, we will consider the data interface service. The DIS is responsible for all communication to and from the module, and as such is installed as a network service. The interface is simple, using text based instructions to send and receive information. However, the service can also be set up to provide advanced features such as encryption and other secure data interfaces.

The second system under consideration is the practical laboratory software. This is a collection of administrative, operational and support tools that together make up a comprehensive software package to run the equipment during practicals. A key element of this tool is that it is just a software package, requiring no speciality hardware to function. Because of this the unit can be installed on any computer system that is compatible with the Linux operating system. Although some speciality interfaces (such as rotary dials and dedicated switches) may be added later, these interfaces will still be designed to connect using USB.

During this chapter we will consider both systems, as well as the variety of users and use cases applicable to each. There are also general considerations for the use of network connected software systems, which we will discuss at the end of the chapter.

8.2 General System Operation Principle

From a user's perspective the module is the smallest element of the system. (This differs from the developer, for whom the mini-module, as discussed in §7.2.3, is the smallest element.) Three parameters determine how we define the configuration of the system, namely the *user location*, *module relation* and *interface type*.

The user location defines where the users are relative to the system they are using. The user location can either be *local*, which means the users are physically next to the system and using the equipment's own sub-network, or they can be *remote*, that is physically removed from the unit but connecting to it through a general Ethernet.

The module relation refers to the way in which the units are connected to each other, which can either be *bunched* or *diffused*. In a bunched system the modules are installed in physical proximity and are located on the system's own subnet, and in a diffused system one or more of the modules are remote, and connected through a general Ethernet.

Lastly, the interface type refers to the way in which the user is communicating with the system, either through a *direct connection* with each module or through the *practical laboratory software package*.

These options allow for eight variations, but not all the various are sensible. Table 8.1 details the six configurations we will be discussing.

Table 8.1: Six possible interface configurations for the system of prototype three.

Configuration	**User Location**	**Module Relation**	**Interface Type**
1	Local	N/A	Direct
2	Remote	N/A	Direct
3	Local	Diffused	Software
4	Remote	Diffused	Software
5	Local	Bunched	Software
6	Remote	Bunched	Software

8.2.1 Configuration 1 and 2: Direct Connected Systems

The modules can be used directly to conduct measurements and observations without the need for a dedicated module to supervise the system. The first two configurations address this type of setup.

Users can connect directly to the module, either by plugging directly into the module's network interface or by connecting to the same network as the module. They can do this from any computer system that is able to communicate using standard Internet Protocols. Using this direct interface they can perform setup operations on the module, as well as instruct it to perform and store measurements.

(The amount of data that the module will be able to buffer internally depends on its installed storage space.)

Since the modules function independently each one must be instructed separately. Also, since the modules do not require each other to function, the network relationship between them is immaterial. Rather, the relationship between the user's computer and each module is the key element, which is why the *module relationship* is discounted for the first two configurations. A local user refers to a user directly connected to the module's interface, whereas a remote user is connected through a shared network.

Because of a limitation of direct access, as well as stand-alone module operation, the modules have no means of connecting to other modules. The third prototype designates that modules should, in general, be complete stand alone experiment systems. In this case all the parameters measured by the module can be downloaded afterwards, and the data can then be synchronised and processed using time-stamp imprinted by the module during recording. However, when multiple experiment modules require shared information in real time (such as a solar photovoltaic panel tester and a heliostat frame controller) the modules must be connected to a central experiment controller.

Like the practical laboratory software package, this experiment controller only needs to exist in software, but will require that it also performs supervisory tasks during the experiment, and remains permanently connected.

8.2.2 Configuration 3 through 6: Connected through the Practical Laboratory Software Package

There are four possible configurations for using the modules as part of a practical education system. The practical controller runs alongside the network module that creates the practical system's sub-network and provides the single external network connection point. It is the relationship of the user and the modules to the practical controller module and the sub-network that determines the configuration.

8.3 The Data Interface Service

The data interface is provided as an installed service within Linux on each module. It is the only way to communicate with a module, and as such it must have a common set of commands that will allow a system to query the module to obtain basic information as well as a list of possible commands. To simplify this process we propose the design of a driver.

The driver will be stored on the module it pertains to. When a device, whether a control module or a user's computer, connects to a new module it can request basic information as well as download its driver. The device can then scan the driver to match input and output formats and data types.

Since modules build on mini-modules, there is a good chance that they could have many shared elements. But, the number and complexity of these elements may differ from module to module. For example, consider an AC voltage measurement mini-module. Even though it might be integrated into a variety of modules with vastly different purposes, it still only measures a voltage. So when a user develops an experiment requiring a voltage measurement it should be possible to connect it with the data from the voltage measurement mini-module regardless of the rest of the module or the remainder of the experiment. This means that rather than build a completely new driver for each module, we will construct it from a collection of smaller drivers, thus simplifying the integration and compatibility.

However, it may be that the voltage measurement mini-module provides additional parameters, such as harmonic measurements. This added functionality must be incorporated without losing compatibility with basic systems. To do this we propose a new intermediary interface called an *Augmentation*. It extends an existing driver by providing additional functionality to it, or by overwriting an existing method. So, the mini-module would still use an AC voltage measurement driver, but would include an augmentation to add the harmonic measurement capability. A basic experiment can then start by scanning the module for drivers, and when it finds the base voltage measurement driver it can stop, whereas advanced experiments can continue scanning to add the additional functionality. This reduces the development time on both the driver and on the software side.

8.4 Practical Laboratory Software Package

The practical laboratory software package is more than just an interface for the measurement equipment, but rather a collection of tools that aims to provide a complete solution for the presentation and administration of practicals. Using the agents identified in earlier chapters, we are able to propose some of the required functionality that will inform the framework and the eventual development.

Three main agents interact with the practical system, namely the lecturers providing the practicals, the students performing them and the administrators who oversee the academic department. When considering new features it is important that the impact on all three agents be considered. We exclude the laboratory staff from the general considerations, but they too must be considered in the software design.

However, the software, like the hardware, does not need to be developed all at once. Because the software is upgradable, including the firmware and direct interfaces, it is possible to correct mistaken developmental choices as well as the upgrade to include new features and compatibilities.

Starting off, the system must allow lecturers the ability to design and present practicals. The next step would be to include remote operation for teaching purposes, and later on for use by students as a remote laboratory. From the lecturer's perspective the system must easily facilitate the development of new practicals, including the integration of media for explanation. During the practicals the system must provide real-time feedback to the lecturer on the progress of each bench, allowing better management of the lecturer's support.

To the student the system must provide a way to easily access and complete the practicals. The system must support the student without taking over the work. Support systems for the student include aspects such as data backups and exports, as well as configurability of experiments and group-work support. It should also allow students to provide regular and detailed feedback on practicals to the lecturer and administrators.

Beyond administering it, this system must attempt to provide as safe an environment as possible. This could also be adapted to meet the various specifications during different times. For example, during a regular practical session some of the protection mechanisms could be relaxed because there will be support staff. However, when the students are working on their own the system could require a minimum clearance from a machine before activation, or could refuse to perform certain experiments because they are too hazardous.

Lastly, the system must provide the ability for a lecturer to take control of various modules during a practical. This could enable a lecturer to do a demonstration on one of the units and have it shown on all the units in the practical simultaneously. The units only transmit the measured data, and leave the rendering of the interface to the computer itself, which differs from streaming a video.

This feature is similar to the class-demonstration system. The class demonstration system should work in a similar manner to the remote laboratory system, but with the key difference that it must allow recording of experiments. This would allow a lecturer to record a practical session, or a specific demonstration, and show that session during class. Or, alternatively, to switch over to live systems feedback.

Finally, to allow the integration of the practical system as a tool for examination, careful consideration has to be given to the challenges surrounding an exam environment.

8.4.1 Example Interface

As with the hardware, we design prototypes to highlight certain features of the software user-interface and to help us find new elements of the design.

The first design (shown in Figure 8.1) shows the opening page of the program.

The interface elements are big, since the system must be designed for use on a touch screen. Also the design is clean. Lots of elements are vying for screen space, and it is important to use a method of gradual disclosure to present new elements of the system, so that the user is not overwhelmed.

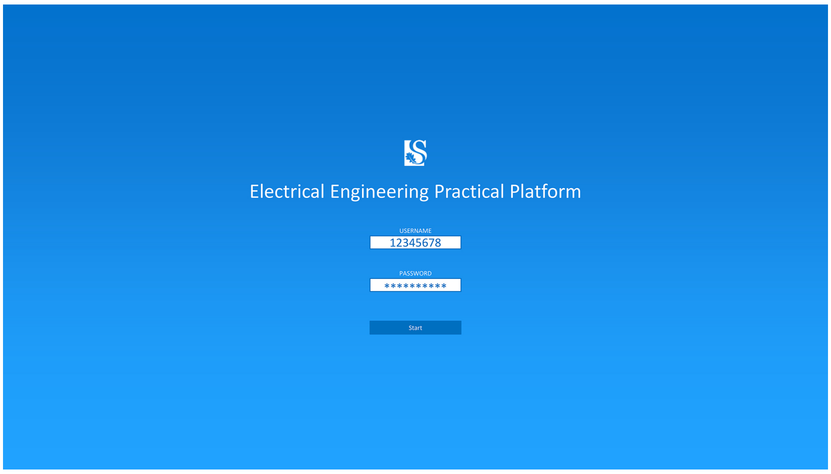
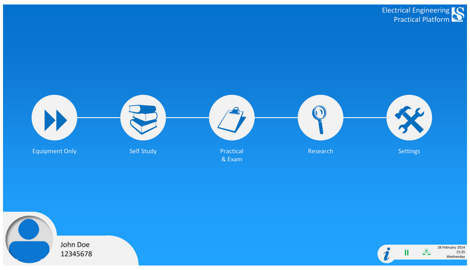
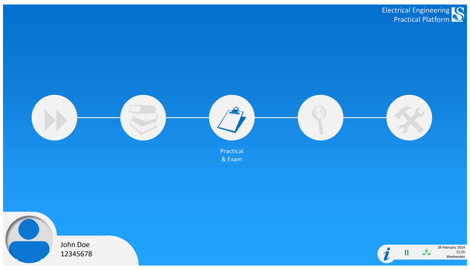


Figure 8.1: Mockup of the log in screen from the third prototype's practical system software user-interface.

The second screen, in Figure 8.2a, shows the default actions when the user enters the program. Some of the options on the home screen might be greyed out, depending on the user's permissions. However, the button is not removed. This transparency of operation makes it clear to the users where the settings or options are, only that they are not permitted to use them. An example of this mode is shown in Figure 8.2b.



(a) First action screen with all options enabled.



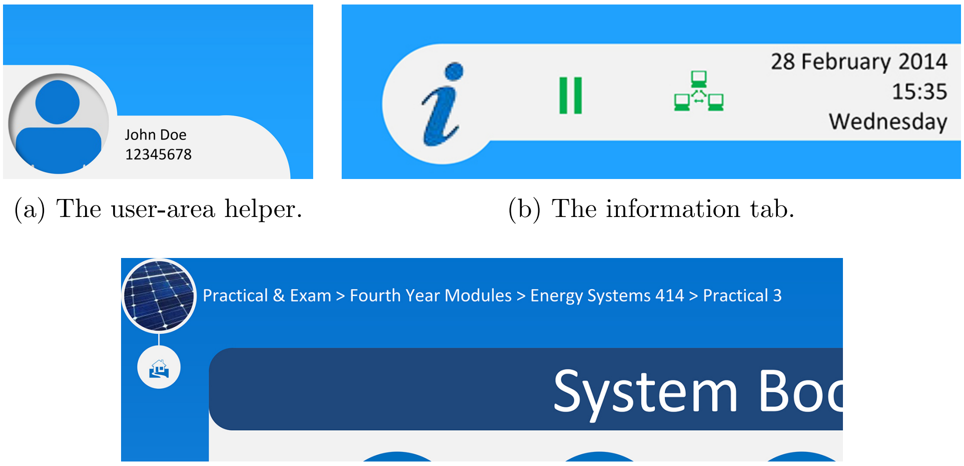
(b) First action screen with options disabled to reflect limited user rights.

Figure 8.2: The home screen of the software package for various permission levels.

Once a user enters the *Practical and Exam* section of the software, there are three screen helpers to assist the user in navigating, managing and using the system. The first is the *user area* located on the bottom left of the screen: see Figure 8.3a. On the master option screens the user name is displayed, next to a large picture, and on busy screens (such as during practicals) the user information is shrunk to only a small portrait without text. This icon can be selected at any stage to access information about the user, change settings, log data, transfer information, etc.

The second helper is the information tab, located at the bottom right of the screen, pictured in Figure 8.3b. This tab shows the user the current status of the system, including the network status, the date and time, as well as the recording status. (In the picture the system is currently not live, and hence the symbol for "pause" is shown.) The user can also select the "i" to access the help files.

The last helper is the navigation bar at the top left of the screen, shown in Figure 8.3c. This indicates the current menu position to the user, helping to navigate the unit.



(a) The user-area helper. (b) The information tab.

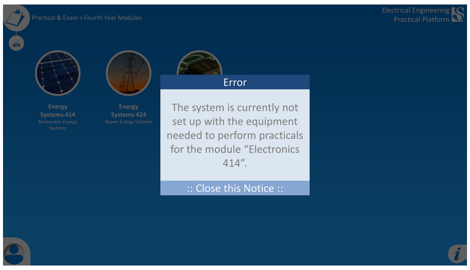
(c) The navigation bar.

Figure 8.3: Various screen helpers of the practical laboratory software package.

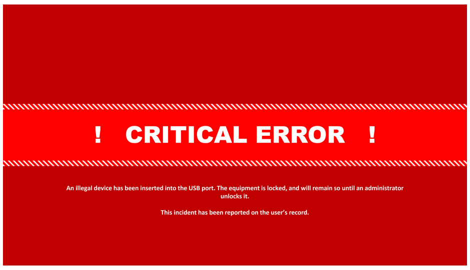
Finally the error screens. There are two kinds of errors, which we will refer to as *mistakes* and *violations*. The former is an error made by the user, but not a serious one, and one that is presumed not to have been made on purpose. This type of error only requires an informational warning to indicate that something has been requested that is not possible, and to give the reason and possible remedy. This could be something as simple as selecting a practical that is not available any longer, or setting the protection on a circuit higher than the circuit is capable.

A violation is a deliberate attempt at circumventing or damaging the system in some way. These types of actions will be recorded in the session log for the specific user, and the warning needs to reflect the severity of the action. The system must also shut down, requiring a lecturer to unlock it.

The difference between a mistake and a violation screen is shown in Figure 8.4a and Figure 8.4b respectively.



(a) An error screen for a *mistake*



(b) An error screen for a *violation*

Figure 8.4: Various error screens of the practical laboratory software package.

8.5 General Challenges

There are numerous advantages to developing a high-level software system as opposed to the basic interfaces that are employed on systems at the moment, but it introduces a significant number of challenges. These challenges must be investigated and addressed before the framework can be implemented.

8.5.1 Security

The security of both the practical laboratory software as well as the direct connection service is of concern to us. According to the 2010/2011 Computer Crime and Security Survey report, a joint effort by the Computer Security Institute (CSI) and the Federal Bureau of Investigation (FBI) of the United States, 41.1%($N = 285$) of respondents stated that they had experienced a security incident during that year. Of these incidents, 21.6% noted that these were efforts directed against their systems. [Computer Security Institute, 2011]

In §6.2.3 we discussed the security from a network interface perspective, but it is equally important to secure the software too. This is true for both the software that will be developed specifically for this project as well as the other software installed on the various modules. The Linux development community continuously release operational and security updates for the various operating systems and services and it is imperative that these be kept updated to ensure that the systems remain functional and safe.

However, a single operating system is only supported for a limited period of time. The Ubuntu operating system, for example, has "Long Term Support" editions, which Canonical commit to supporting for a period of five years. [Ubuntu Wiki, 2013] However, once this period expires the software has to be updated to a newer version to continue receiving security updates.

This poses a problem for the developer. For a personal computer (and more so for a server) it is reasonable that the equipment will be replaced within five years, since the system will become obsolete. However, this is not the case for the practical support system. Given that the experiments it will be controlling are unlikely to change as often, it is foreseeable that although new experiment support modules may be added, the old ones do not necessarily need to be replaced. In the case of dedicated hardware the software becomes obsolete before the equipment does, but although replacing the software itself is free, the hardware is not. Even though the Small Single Board Computer can easily be replaced within each module, there is a development cost on rebuilding the practical system's software.

8.5.2 Updates and Patching

The advantage of having a high-level software program is that it is easy to update; unlike firmware that often requires access to microcomputer in-circuit programmers and is risky, considering that a problem during upload can cause the system to cease functioning.

This allows developers to add features as well as find and fix bugs in the software. However, as with the updating of the operating system, it will be necessary to do this type of maintenance regularly to ensure that all the modules are stable and safe to use. The problem is that this can entail a laboratory technician spending an inordinate amount of time just on updating modules' software. Assuming our four module system from the solar energy practicals example, and 20 workstations in the laboratory, then there are 80 modules that will need to be updated.

For the system to be sustainable it will be necessary to automate the updating process, as well as to provide laboratory managers with their own set of software tools to monitor and maintain equipment.

8.5.3 Storage and Backups

Each practical system will store information ranging from student attendance to real-time practical progress recordings as well as measurements of experiments for download and use by the students in reports. It also needs to store all the practicals, help files, as well as any media that lecturers have provided as additional content for a practical.

Students will, however, not necessarily work at the same practical workbench, or in the same group, every time. So their information cannot be stored only in a single practical setup. The system will require a server to store the information, which can then be downloaded as a student logs into a specific system.

But, this is not required for the first iteration of the system, and should be carefully considered as the introduction of a central information repository (specifically one that stores personal user information) must be thoroughly assessed and researched to ensure a secure and robust solution.

One additional problem of a central information repository is that the practicals and exams now become dependent on the availability of the university's network infrastructure. A possible solution is to have the system save an encrypted file onto a user's flash drive. This way a session can be set up and operated using only a flash drive.

Such a solution would also allow a lecturer to prepare a collection of special exam users that each have a specific experiment loaded, as well as a series of questions and other tasks. As students enter the laboratory for the exam each one is handed a flash drive and can immediately start working. All aspects of the exam are recorded on the flash drive and can be reviewed afterwards only by the lecturer. This would also allow the laboratory staff to disconnect the units from the general university Ethernet during exams.

8.6 Chapter Summary

In this chapter we introduced the requirements and challenges of both the direct connect service as well as the practical laboratory software package. We identified the various configuration options of the system, and used these to discuss both the software as well as the users and their requirements.

Even though the software development itself falls outside the scope of this study, it should be clear that the required software systems are expansive and complex and will require substantial research before it can be included into the development framework. The framework will not only have to consider the software tools, but also the maintainability, upgrading, security and more.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

Through the course of this thesis we have been able to address the problem of designing practical engineering education systems from a variety of angles. We have considered the current literature, as well as evaluated systems that are currently being proposed both in the academic sphere as well as in the commercial market place.

We conducted extensive interviews with the academic staff, the students, the support staff in the laboratories as well as the graduate students who work alongside lecturers as teaching assistants during practicals. We also made observations in a variety of practical engineering education settings. Furthermore, we were able to integrate material from both the interviews and the observations into several prototypes towards a system for practical engineering education.

In terms of the equipment we designed and developed three prototypes, as well as investigated the design and development of the software front-end and the module data interface. Although the construction of physical prototypes was limited by a lack of development funds, our aim was not to build physical systems but to gain the necessary insight into the challenges of such a design that would help shape a framework for the development of a complete system.

The hypothesis of our research was that:

> *It is possible to distill the requirements of a system that would be able to meet the needs of the modern laboratory into a framework that will guide development, thus allowing for continuous improvement and lowering costs, without compromising quality or safety.*

Through the research presented, this hypothesis holds true. We have successfully defined the parameters of the modern laboratory through an in-depth investigation of the requirements of all the various agents working there. The development of a system for practical engineering education is plausible, but only through adherence to a framework that provides structure to the effort. The literature shows a multitude of initiatives that have started with good intention and audacious goals, only to fade away due to a lack of a focussed development guideline.

9.2 Summary of Contributions

Through a detailed literature study, interviews, observations and three prototype developments we were able to detail the design process for engineering education systems development. This can now be incorporated into a framework for the development of the described system, or the approach can be used to investigate other systems in education design and development.

One of our major contributions was to introduce the field of engineering education research to engineering researchers, particularly in South Africa. And, to a lesser extent we have also provided an insight into the engineering design and development of systems to readers from the education research fields. Our hope is that this inspires conversation between the two disciplines, and hopefully results in groups from both sides embarking on projects together that seek to address the challenges of education systems designs.

The study of engineering education is a well-established field in many developed nations, particularly in the United States of America, Australia, Germany and the United Kingdom. However, in South Africa there has been very little development on this front. A major challenge for engineering researchers who want to enter the field of education research is the sheer scale of the field. Through the thorough history and literature study presented here, our work will help to orientate new readers.

Lastly, we contributed to the development methodology itself by introducing concepts from the fields of design and industrial psychology, intertwining them with the current engineering perspectives on system development. Education systems development is not a purely technical challenge, but is the design of a system that will always be used by people, and interfaced with them. The system is not built for any form of autonomous operation, and as such the user must form a vital part of the design equation. We helped to develop this balance between robust, cost-effective and functional electronics and a system that is usable, practical and aesthetically pleasing to its users.

9.3 Recommendations for Future Work

This was an exploratory study, and as such there is room for improvement and expansion in almost every aspect of the work. Throughout the thesis we have highlighted areas where we have had to limit our research, and completing or expanding on these sections is a natural starting point that would serve to further clarify the understanding of the material discussed here.

Beside the aforementioned aspects, there are three areas in particular that we feel warrant further research: the current engineering curriculum; the legal frameworks; and the software front-end.

The **Current Engineering Curriculum** pertains to the section of work where we conducted staff and student interviews, as well as investigated the current academic offering at Stellenbosch University as an example of engineering education in South Africa. This study should be expanded to include other South African universities, thus providing a more comprehensive view of engineering education in South Africa.

The **Legal Frameworks** refer to investigating of the current legal aspects surrounding intellectual property rights when considering the development of open-source hardware. The question of true ownership needs to be investigated, especially considering the involvement of organisations such as the South African National Government and their stringent licensing of intellectual property stemming from research funded by public money. A detailed study is needed to first investigate the legal frameworks currently in place, then to identify the requirements and finally to develop a legal road-map that could be incorporated into the framework to support the proposed development.

Finally, the **Software Front-End** requires a more detailed analysis of the various systems for interconnection that would allow a complex system to be built robustly, securely and in ways that promote the modularity of the system. Particular attention must be paid to the security and encryption requirements, to ensure a much better understanding before it is incorporated into the development framework.

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Appendix A

Practicals for Energy Systems 414 from 2012 to 2014

A.1 Practicals for 2012

The practicals are reproduced here with permission from the author, Pieter C. Oosthuizen as well as the University of Stellenbosch, Department of Electrical and Electronic Engineering.

The names and information of all students, as well as the contact information of the lecturers, has been removed. Since this information was used only to allow students to contact lecturers, as well as to assign students to groups, we are confident that it does not detract from the content and the purpose of publication here.

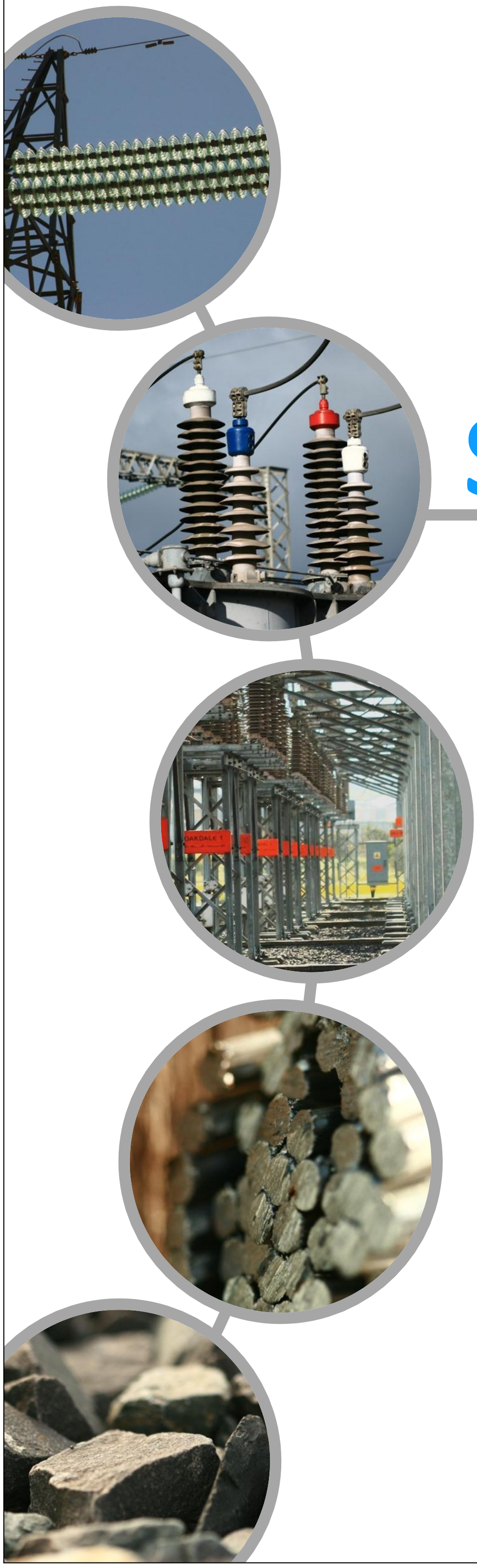
Practical 1: Introduction to basics of the solar energy resource. (§A.1.1)

Practical 2: Study of the materials and equipment used to convert the solar resource into electrical energy. (§A.1.2)

Practical 3: Investigating the use of solar energy with various system types. (§A.1.3)

Practical 4 (The Design Project): Design of a solar energy solution for a simulated engineering problem. (§A.1.4)

A.1.1 Practical 1



Department of Electrical and Electronic Engineering

ENERGY SYSTEMS 414

Solar Practical 1 :: 2012

Title:	**The Sun as Solar Resource**
Date of Practical:	10 April 2012
Practical Starts:	14:00
Practical Venue:	Meet in E&E Auditorium (E203) Proceed to 4th Floor Telecoms Lab.
***Author*:**	Pieter C. Oosthuizen
***Contact Time*:**	3h
***Self-Work Time*:**	6h
Assessment Type:	Report

Stellenbosch University

Part 1: Practical Information

1 Introduction

1.1 Practical Overview

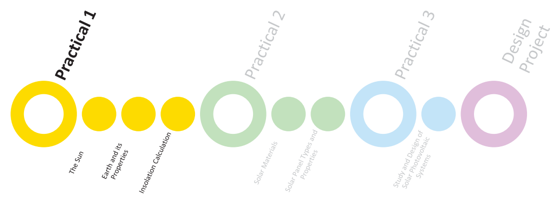
The aim of this practical is to provide you with a chance to study the basics of the solar energy resource. Through a theoretical approach this practical will support you in developing a deep understanding of:

- The Sun as an energy resource
- The influence of the Earth's atmosphere, orbit, spin and axial tilt on the solar resource
- The various ways that we can optimize the geometry of collectors to maximise solar collection.

This practical does so by having you develop the various aspects of the solar resource into a set of computer algorithms to be used in coming practicals and projects. Each of the aspects of the resource will be discussed and an algorithm developed for it – which will then be tested and evaluated by using that tool to solve a series of related problems.

1.2 Practical Series

This practical is the opening practical for the Renewable Solar Energy Practical Set. The path is outlined below:



Each practical builds on the previous one, so please ensure that you hand in your work in a timely fashion, and complete the assignments as accurately as possible. Throughout the 3 practicals you will be developing tools that will be used to complete the Design Project – as such it is recommended that you document your work as accurately and as thoroughly as possible.

2 Practical Properties

Property	Value
Date of Practical	10 April 2012
Practical Time Slot	14:00 to 17:00
Practical Location	Meet in E203 (Auditorium) then to Telecoms Lab
Practical Contact Session Duration	3 Hours
Total Time Outside Practical Recommended to Complete Practical	6 Hours
Assumed Knowledge[1]	• Basic Matlab ○ Using Variables ○ Using Matrices ○ Writing Functions ○ Generating Output to Graphs ○ Using Help and Support • Flow Diagrams
Workgroup Size	Individual Practicals
Assessment	Submitted Report (See §2.1 for details)
Submission Date	Friday, 13 April 2012 **before** 16:30
Submitted To	Ms Charlene Weimers (Administrative Officer) 3rd Floor E&E Building

2.1 Assessment

The practical will be assessed based on a printed report, submitted before the deadline. Please note that the report must be neatly presented. No hand-written work will be accepted. Communication skills form an integral part of any engineering task, and as such it will also be evaluated as an integral part of the report.

If it is deemed that the report, or the work it is reporting on, is not of high enough standard then the student will be requested to resubmit their report. Failure to obtain a pass grade for the report, and as such the practical, will result in an incomplete for the module as defined in the module framework.

The practical report will be returned to the student during class by the Monday after the submission date.

2.2 Venue

Students meet for an introductory session in the Auditorium (E203). The practical will be conducted in the 4th floor Electronic Classroom.

2.3 Teams

This practical is for self-study – no teamwork will be allowed. Furthermore each student must submit their own report.

[1] It is assumed that the student has the following knowledge. If the student falls short of this requirement then it is their responsibility to ensure that they study up on this material before the practical.

3 Resources

3.1 Required Reading

It is required of each student to ensure that they are familiar with the concepts discussed during class, as well as the material presented in chapter 7 of *Renewable and Efficient Electric Power Systems* by *Gilbert M. Masters*.

3.2 Preparation Required

The student must bring to the practical:

- *Renewable and Efficient Electric Power Systems* by *Gilbert M. Masters*
- Any class notes based on the work from Chapter 7 in *Masters*.
- Scientific Calculator for spot-checking of results
- Pen-and-paper for drawing and writing

Part 2: Content

4 Solar Path

4.1 The Earth's Orbit

To accurately determine the position of the Sun, we first need to study the Earth's orbit around it. We start by examining the formula to describe the earths distance from the sun. **Using Matlab program the following function:**

$$d = 1.5 \times 10^8 \left\{1 + 0.017 \sin\left[\frac{360(n-93)}{365}\right]\right\} \qquad \text{Km}$$

Please ensure that your code is properly commented and include a copy of the code as an addendum to your report. (This must be done for all code written in this practical.)

Using this function, please complete the following:

a. **Write a function to find the perihelion.**
b. **Write a function to find the aphelion.**
c. **The solar energy reaching the Earth from the Sun is inverse proportional to the square of the distance between the two bodies. What is the attenuation of solar power between the Sun and the Earth when the Earth is at the perihelion? (Express your answer in decibels.)**
d. **Calculate the difference in solar power reaching the Earth between the perihelion and the aphelion. (Express your answer as the percentage loss between the maximum and minimum values.)**

4.2 Altitude Angle of the Sun at Solar Noon

4.2.1 Solar Declination Angle

We need to program the function that will allow us to determine the Sun's position at any time of day. It is important that we have a function that will provide the solar declination angle anywhere on Earth, northern- and southern hemispheres.

The following formula calculates the solar declination for any given day in the northern-hemisphere:

$$\delta = 23.45 \sin\left[\frac{360}{365}(n-81)\right]$$

To obtain the formula for the southern-hemisphere we simply centre the sinusoidal oscillation around the spring solstice for the southern-hemisphere, namely 21 September.

Write a Matlab function that will calculate the solar declination, with a parameter option to select either Northern or Southern hemisphere.

Check your function by comparing it to the following values:

	Jan	Feb	Mar	Apr	May	Jun
Northern	-23.0	-17.5	-8.3	4.0	14.9	22.0
Southern	23.1	17.9	8.9	-3.4	-14.4	-21.8

	Jul	Aug	Sep	Oct	Nov	Dec
Northern	23.1	17.9	7.7	-4.2	-15.4	-22.1
Southern	-23.2	-18.3	-8.3	3.6	14.9	21.9

Using this function, please complete the following:

a. **Combine on a single graph the annual declination angles for both the northern- and southern-hemispheres, using a 1-day resolution.**

4.2.2 Solar Declination Angle Relative to the Horizon

The next step is to use this formula to calculate the solar altitude angle which is the angle of the sun relative to the local horizon.

Write a Matlab function that will invoke your previous function to produce the solar altitude angle. Remember that you function has to automatically use the correct solar attitude based on the sign of the user provided latitude. (Latitudes are specified as positive for the northern-hemisphere and negative for the southern-hemisphere, with the equator at 0°.)

4.3 Solar position at any time of day

We are now able to calculate the position of the sun at solar-noon, however in order to accurately determine the yield and efficiency of solar equipment, we need to be able to calculate it at any time of day.

The first step is to write a formula that will calculate the *hour angle* for any given time. Adapt the following formula to use hours, minutes and seconds:

$$Hour\ Angle\ H = \left(\frac{15°}{hour}\right) \times (hours\ before\ solar\ noon)$$

Write a Matlab function that will provide the Hour Angle, but change your formula to be accurate to a second.

The next step is to determine the position of the sun.

Use the following formulas to write a Matlab function that returns an array containing the azimuth and altitude of the sun given the time of day, day of the year and latitude of a specific point on earth.

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta$$

$$\sin\phi_S = \frac{\cos\delta \sin H}{\cos\beta}$$

Using this function, please complete the following:

a. **Complete Example 7.3 in the book using your own formula.**

b. **Repeat Example 7.3 for the following locations, dates and times:**

	Location	Day	Solar Time
i	Cape Town	1 Jan	08:00
ii	Bloemfontein	23 July	06:00
iii	Perth, Australia	10 December	18:00
iv	Tokyo, Japan	21 September	11:00
v	SANAE IV Research Base, Antarctica	10 Jan	05:00

4.4 Sun Path Diagrams

The next step is to develop a function that will plot a Sun path diagram. We must be able to do this for any place on Earth so that we may analyse the specific site for its feasibility as a solar-energy site.

Using the functions developed in the previous exercises, write a function that will draw a sun-path diagram similar to figure 7.12 (page 399) in the textbook to indicate the sun path during various times of the year.

The user must be able to specify the number of intermittent curves that they want on the graph, from 0 indicating that they only want the highest and lowest curves, to 182, indicating that they want every day possibly available. A separate function must also be developed to allow a user to print only a specific day.

You do not need to plot the text associated with each curve, but must print all the other legends. Remember that the title of you graph must clearly indicate all the parameters of the printed graph.

4.5 Civil Time

Using Matlab write a function that is able to convert any given solar time, along with its local time meridian to the correct local time. (Daylight savings excluded.)

4.6 Sunrise and Sunset

Using Matlab write a function that will give the actual sunrise and sunset times given the location, date and time.

5 Insolation

5.1 Extra-terrestrial Solar Radiation

Given the following formula:

$$I_0 = SC \times \left[1 + 0.034\cos\left(\frac{360n}{365}\right)\right]$$

Use Matlab to write a function that calculates the extra-terrestrial solar radiation for a given day, *n*, expressed as the number of days from the start of the year.

5.2 Atmospheric Attenuation

Given the following formula to model atmospheric attenuation:

$$I_B = Ae^{-km}$$

Use Matlab to write a function that calculates the portion of the sun's rays reaching the Earth on a specific day, specified as n.

For m, A and k, please use the following equations:

$$m = \frac{1}{\sin\beta}$$

$$A = 1160 + 75\sin\left[\frac{360}{365}(n - 275)\right]$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n - 100)\right]$$

5.3 Total Clear Sky Insolation on a Collecting Surface

We must now determine the total incoming energy on a solar collector.

Using Matlab write a function that will provide a vector for the total energy inbound on a collector, where we specify the following:

- **Collector's elevation angle**
- **Collector's tilt angle**
- **Current Latitude**
- **Day of the Year**
- **Time of Day**
- **Reflectance of the Ground Surface**

The output of this function must be a vector in the following format: (All Units in W/m^2)

$$\boldsymbol{P} = \begin{bmatrix} Direct\ Beam\ Radiation \\ Diffuse\ Radiation \\ Reflected\ Radiation \\ Total\ Radiation \end{bmatrix}$$

5.4 Tracking Systems

Now we need to adapt our formula to calculate the available radiated solar power vector when using stationary solar panels, single axis trackers and dual axis trackers.

Using Matlab write a function that will provide the available radiated power vector for a system where the user can enter one of the following:

- **0 - Stationary Solar Panels**
- **1 - Single Axis Solar Tracker (Horizontal Tracker)**
- **2 - Dual Axis Solar Tracker**

The output vector must be the same as in §5.3.

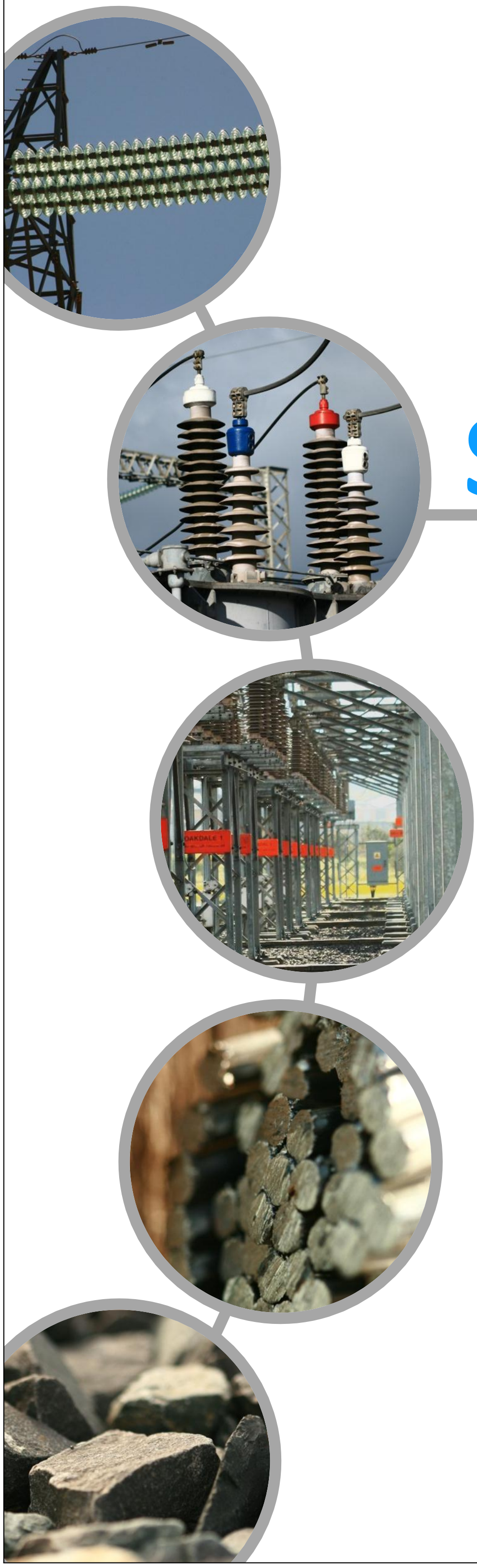
6 Monthly Clear-Sky Insolation Graphs

We need an algorithm that will be able to print out a graph of the potential radiated solar energy on a solar panel over an extended timeframe.

Using Matlab develop a function that will allow a user to enter all relevant information about a solar panel site, along with a start date (specified as a number counting the days from the start of a year) and end date and then be able to plot the resulting power on a graph ready for printing.

Please use your own discretion here with regards to what you think will be necessary for such a tool. Remember that you will be the end user of this tool in the weeks to come.

A.1.2 Practical 2



Department of Electrical and Electronic Engineering

ENERGY SYSTEMS 414

Solar Practical 2 :: 2012

Title:	**Photovoltaic Materials and Electrical Properties**
Date of Practical:	17 April 2012
Practical Starts:	14:00
Practical Venue:	Meet in Electrical Machines Lab
***Author*:**	Pieter C. Oosthuizen
***Contact Time*:**	3h
***Self-Work Time*:**	6h
Assessment Type:	Report

Stellenbosch University

Table of Contents

Part 1: Practical Information

1 Introduction

1.1 Practical Overview

In the previous practical you investigated the Sun as a source of energy. In this practical we will be investigating the materials and equipment that is used to convert the Sun's photonic energy into electrical energy.

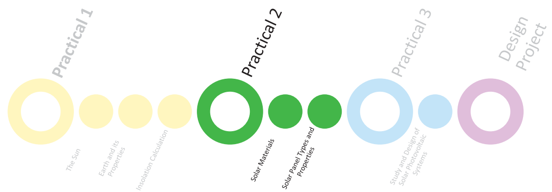
This practical aims to help you develop a feeling for the correlation between the theories as presented in the literature, and the real world applications and practice. The practical also builds on the ideas developed in the first practical by demonstrating the use of some of the formulas developed during that practical. If you are diligent and thorough with the theoretical component as well as the practical elements of this practical then it will help you a great deal in developing a deep understanding of:

- Basic semi-conductor physics
- Basics of photovoltaic cells including equivalent circuits
- Reaction of PV modules to tilt and elevation
- Movement speed of the sun and its effect on stationary panels
- Voltage-Current relationship of various solar module types
- Impact of Shading on various solar module types

Note: The practical starts with a purely theoretical approach, and gradually expands to allow theoretical prediction of the results of a proposed experiment, which is then verified by a practical experiment. The aim is to help you to develop your understanding of solar technology by comparing your predictions to the measured results and attempting to understand the discrepancy where present. Where requested, please ensure that you do make the prediction before you actually perform the experiment as this is for your own benefit.

1.2 Practical Series

This practical is the second practical for the Renewable Solar Energy Practical Set. The path is outlined below:



Each practical builds on the previous one, so please ensure that you hand in your work in a timely fashion, and complete the assignments as accurately as possible. Throughout the 3 practicals you will be developing tools that will be used to complete the Design Project – as such it is recommended that you document your work as accurately and as thoroughly as possible.

2 Practical Properties

Property	Value
Date of Practical	17 April 2012
Practical Time Slot	14:00 to 17:00
Practical Location	Meet in Electrical Machines Lab
Practical Contact Session Duration	3 Hours
Total Time Outside Practical Recommended to Complete Practical	6 Hours
Assumed Knowledge[1]	• Working knowledge of the formulas and information presented as part of *Solar Practical 1: The Sun as Solar Resource*
Workgroup Size	Groups of 3
Assessment	Individually Submitted Report (See §2.1 for details)
Submission Date	Monday, 23 April 2012 **before** 16:30
Submitted To	Ms Charlene Weimers (Administrative Officer) 3rd Floor E&E Building

2.1 Assessment

The practical will be assessed based on a printed report, submitted before the deadline. Note that each student is responsible for writing, and submitting, their own report despite the work during the practical being done in groups. Please ensure that you clearly indicate who your team members were. The practical measurements and methodology can be shared, but all theoretical work and other answers must be your own work.

Please note that the report must be neatly presented. No hand-written work will be accepted. Communication skills form an integral part of any engineering task, and as such it will also be evaluated as an integral part of the report.

If it is deemed that the report, or the work it is reporting on, is not of high enough standard then the student will be requested to resubmit their report. Failure to obtain a pass grade for the report, and as such the practical, will result in an incomplete for the module as defined in the module framework.

The practical report will be returned to the student during class by the Monday after the submission date.

2.2 Venue

The practical will take place in the Electrical Machines Lab where the practical starts at 14:00 sharp.

2.3 Teams

This practical itself is performed in groups of three. However, as stipulated in §2.1 each student must submit their own report.

[1] It is assumed that the student has the following knowledge. If the student falls short of this requirement then it is their responsibility to ensure that they study up on this material before the practical.

3 Resources

3.1 Required Reading

It is required of each student to ensure that they are familiar with the concepts discussed during class, as well as the material presented in chapter 8 of *Renewable and Efficient Electric Power Systems* by *Gilbert M. Masters*.

3.2 Preparation Required

The student must bring to the practical:

- *Renewable and Efficient Electric Power Systems* by *Gilbert M. Masters*
- Any class notes based on the work from Chapter 8 in *Masters*.
- Scientific Calculator for spot-checking of results
- Pen-and-paper for drawing and writing
- Sunglasses

Part 2: Content

4 Basic Semiconductor Physics

In this section we will take a look at a series of theoretical questions regarding basic photovoltaic semiconductor physics. The work in this section forms the basis upon which a lot of the work is based.

4.1 The Band Gap Energy

a) Do Masters Example 8.1 on page 452.
b) Do Masters Problem 8.1 on page 502.

4.2 The Solar Spectrum and the impact of the Band-Gap on PV Efficiency

a) Provide your informed engineering opinion about the following statement: When sending crafts to outer space we need to use different solar cell technology than what we would use on Earth.

4.3 The P-N Junction and Junction Diode

a) Do Masters Example 8.2 on page 459.
b) Do Masters Problem 8.2 on page 502.
c) You are approached as a field expert by the press who are currently running a story on renewable energy technology. They are running an article entitled "Solar Panel – see the physics shine through" and want you to provide them with a short 350 word article explaining the basic functioning of solar panels to their laymen audience. Please provide me with your article[2].

[2] You can assume that your manager has already agreed to it on your behalf – so sorry, there will be no backing out of this one.

5 Generic Photovoltaic Technology

In this section we are looking at the characteristics of the individual cells. In the next section we will be expanding on this theory to build an entire solar module, and characterise it by expanding the theory developed here into a more complex[3] structure.

5.1 Simplified Electrical Equivalent Circuit

a) Do Masters Example 8.3 on page 463.
b) Do Masters Problem 8.3 on page 502.

5.2 A More Accurate Equivalent Circuit for a PV Cell

a) Do Masters Problem 8.4 on page 502.
b) Do Masters Problem 8.5 on page 503.
c) Do Masters Problem 8.6 on page 503.

[3] Remember that "Complex" is defined as: *(Adjective) Consisting of many different and connected parts.* Think apartment complex, as in 'of many apartments' and not 'difficult apartments'. It is meant to convey that the larger system is made up of a collection of the smaller items, not that it becomes difficult in some way.

6 Solar Modules and Associated V-I Curves

Now that we have sufficiently developed our theoretical understanding of the basics of solar energy systems it is time to move on to a more practical understanding. In this section we are going to be studying the properties of a couple of solar modules of various technologies.

For the experiments in this practical, as with all experiments, we follow the scientific method:

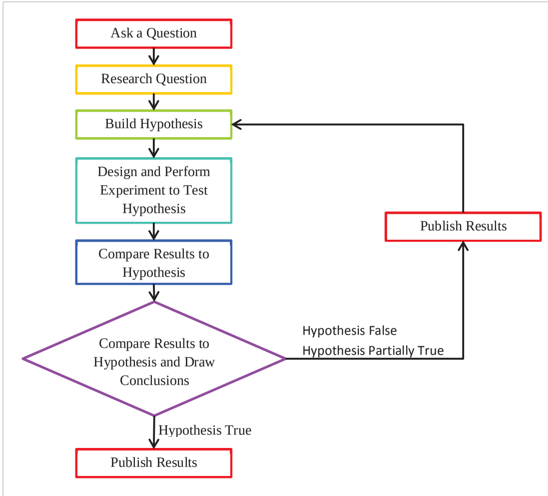


Figure 1: The Scientific Method

6.1 Experiment 1: The Impact of a Panels Position on its Power Output

In Solar Practical 1 we studies the formulas used to predict the position of the Sun relative to our position on Earth. We were also able to determine what theoretical effect the tilt and elevation angle of the solar panel has on the obtained power.

6.1.1 Research Question

What is the effect of the tilt and elevation angle of a solar panel on its output power?

6.1.2 Research and Hypothesis

The Engineering Faculty is located at:

- Longitude: 18°52'0.15" E
- Latitude: 33°55'43.59" S

Using the work from Solar Practical 1 develop your own hypothesis for this experiment.

6.1.3 Design and Perform Experiment

We will be using a First Solar FS Series 3 PV Module, specifically the FS-380, to experimentally verify the effect of tilt and elevation on the solar module output.

For this experiment you need:

- 1 x FS-380 Panel
- 1 x Digital Multimeter (and associated cables)
- 2 x Protractors (Printed as Addendums)
- 1 x Sheet of A4 Paper
- 1 x Kebab Stick
- 1 x Eraser

6.1.3.1 Step 1: Find a suitable location

Take all the items required for the experiment and find an area outside the laboratory that is not shaded. Take a laboratory chair along.

6.1.3.2 Step 2: Measure the current Solar Angles

In order to do this we construct a set of very crude, but very effective, tools.

Start by measuring the solar azimuth angle, ϕ_S. Start by inserting the sharp point of the kebab stick into the eraser. Now place the 360° protractor on the lab chair, and place the kebab stick in the middle. Ensure that the protractor is pointing due north. **Now you are able to read of the azimuth angle.**

The second step is to measure the solar altitude angle, β. We do this by constructing our own Pyrheliometer. Roll the A4 sheet lengthwise to create a paper tube about 1cm or less in diameter. (A smaller device diameter will result in a much better angle, but means much more accurate work is needed.)

To use the Pyrheliometer simply tilt the device so that the Sun's rays can flow "through" the device. In other words, the ideal solution would be to turn it in such a way that you do not see a projected

shadow when holding another surface behind the tube. **When you see the smallest possible shadow you can read of the altitude angle.**

6.1.3.3 Step 3: Measure the Solar Panel at Ideal Conditions

Place your solar panel at the ideal tilt and elevation angles. **Record the open circuit voltage.**

6.1.3.4 Step 4: Measure the Impact of Changing Panel Tilt Angles

Reposition the solar panel at various tilt angles, ranging from optimal tilt angle ±90° in 10° intervals. Keep the elevation angle equal to the optimal angle. **Record the open circuit voltage at each position.**

6.1.3.5 Step 5: Measure the Impact of Changing Panel Elevation Angles

Reposition the solar panel at various elevation angles, ranging from flat horizontal to 90° upright, in 15° intervals. Keep the tilt angle equal to the optimal angle. **Record the open circuit voltage at each position.**

6.1.4 Compile Results, Compare to Hypothesis and Publish Findings

Compile all the results and compare them to your hypothesis. Draw conclusions based on your experimental data.

6.2 Experiment 2: V-I Curve of a Solar Module at Optimal Tilt and Elevation

We have determined the optimum position for the solar panel, now we need to determine the optimum conditions. In order for us to do so we need to determine the V-I curve of our panel at ideal conditions. Normally we would use the Standard Testing Conditions, but this requires access to a very expensive solar light simulator, which unfortunately, we do not have.

As part of this experiment we would like to see if the V-I curve of a real panel differs from the theoretical prediction for the curve.

6.2.1 Research Question:

Is there a difference between the V-I curve of a real panel vs. the theoretical prediction for it?

6.2.2 Research and Hypothesis

a) Do Masters Example 8.4 on page 469.
b) Do Masters Problem 8.8 on page 504.

Using the theory so far, develop your own hypothesis for this experiment.

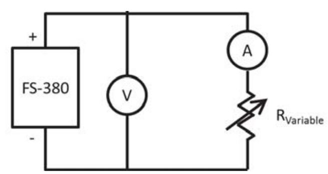
6.2.3 Design and Perform Experiment

We are going to use an adaptable load to obtain our various values.

For this experiment you need:

- 1 x FS-380 Panel
- 2 x Digital Multimeter (and associated cables)
- 1 x 100 Ω Variable Resistor

6.2.3.1 Step 1: Build the Circuit



6.2.3.2 Step 2: Position the Panel

Position the panel to the optimal angle and keep it steady during the entire experiment.

6.2.3.3 Step 3: Record the Values

Step through the entire 55 V range, recording at least 15 points, by using the variable resistor. First record the two boundary conditions, namely open-circuit and short-circuit values. Then record a series of 13 points between these two extremes.

Record the voltage, current and resistor values for each of the data points.

6.2.4 Compile Results, Compare to Hypothesis and Publish Findings

Compile all the results and compare them to your hypothesis. Draw conclusions based on your experimental data.

6.3 Experiment 3: Investigation of the Effects of Shading on Various Solar PV Technologies

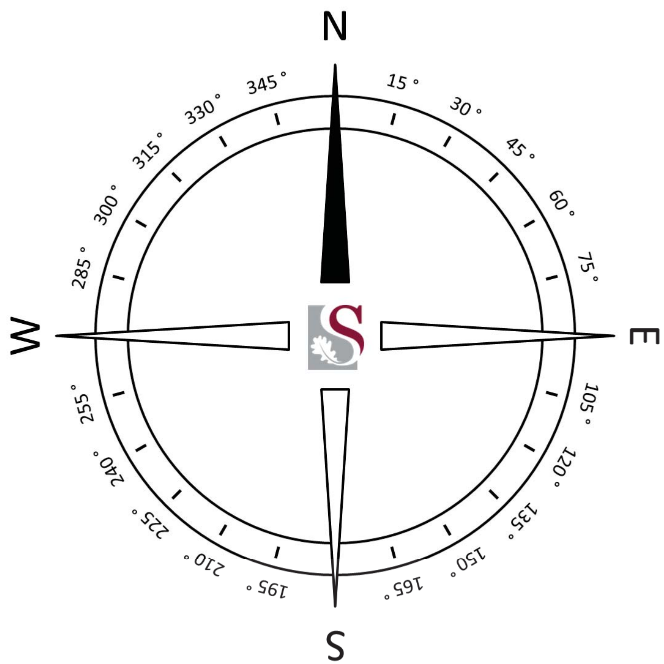
We need to investigate what effect shading has on the performance of a solar panel, and specifically how this differs between various technologies. In order for you to do this experiment properly you are also provided with another solar panel, namely a Centro Solar, Solara S 200M36 Ultra. This is a smaller 22 W_p panel. Ensure that you take note of its nameplate values.

Set-up and perform an experiment to investigate the effects of shading on various solar PV technologies.

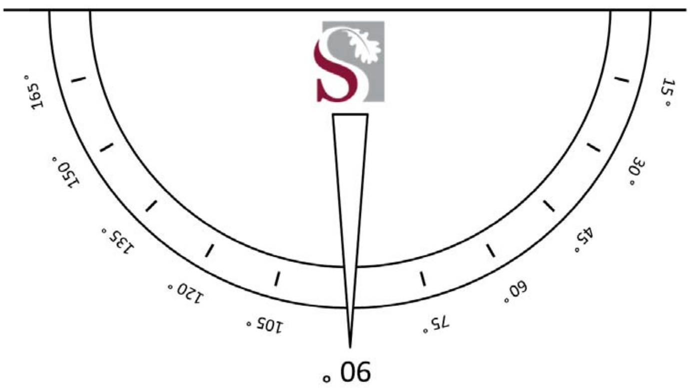
As part of this Experiment please ensure that you also complete the following:

a) **Do Masters Problem 8.9 on page 504.**

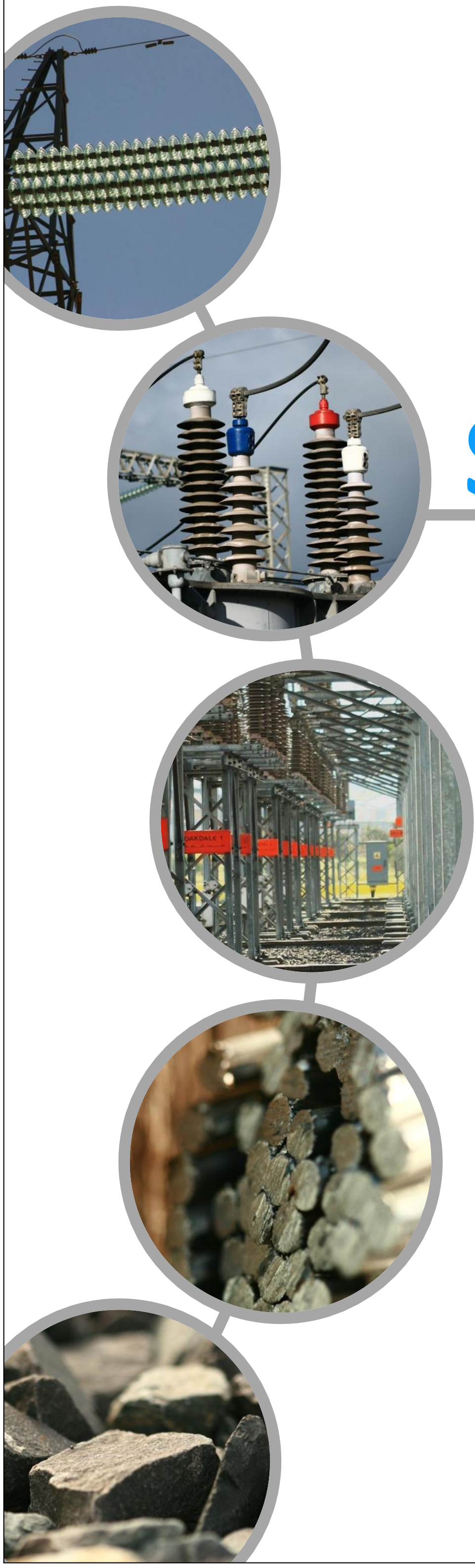
Addendum A: 360° Protractor



Addendum B: 180° Protractor



A.1.3 Practical 3 (redacted copy)



Department of Electrical and Electronic Engineering

ENERGY SYSTEMS 414

Solar Practical 3 :: 2012

Title: **Photovoltaic Systems**

Date of Practical: 24 April 2012

Practical Starts: 14:00

Practical Venue: Meet in E203 (Auditorium)

***Author*:** Pieter C. Oosthuizen

***Contact Time*:** 0.5 h
***Self-Work Time*:** 8.5 h
Assessment Type: Report and Presentation

Stellenbosch University

Table of Contents

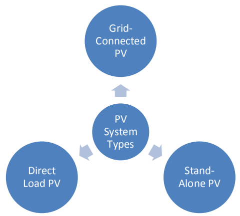
Part 1: Practical Information

1 Introduction

1.1 Practical Overview

In the previous two practicals of this series you investigated the solar resource, and the photovoltaic conversion mechanisms. We now have the tools and knowledge to understand the available energy at a specific location, as well as the technology that will allow us to extract that energy as electrical energy in the most effective way possible, depending on the need. The next step is to design the systems that will use that energy.

When using solar panels we can divide our activities into three broad categories:

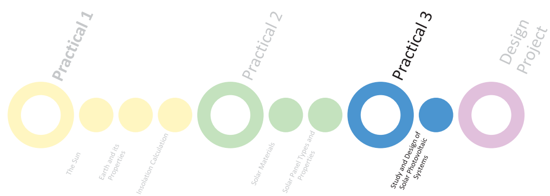


Naturally each of these categories has their own advantages, as well as disadvantages – it is up to the engineer to weigh the various options and make the right decisions.

In this practical you will be facilitating your own learning. During the previous two practical you have been learning about the sun and the energy conversion mechanism, but, you have also been learning a structure whereby new work can be disseminated, studied and understood. It is now time to apply that knowledge yourself.

1.2 Practical Series

This practical is the third practical for the Renewable Solar Energy Practical Set. The path is outlined below:



Each practical builds on the previous one, so please ensure that you hand in your work in a timely fashion, and complete the assignments as accurately as possible. Throughout the 3 practicals you will be developing tools that will be used to complete the Design Project – as such it is recommended that you document your work as accurately and as thoroughly as possible.

2 Practical Properties

Property	Value
Date of Practical	24 April 2012
Practical Time Slot	14:00 to 17:00
Practical Location	Meet in E203 (Auditorium)
Practical Contact Session Duration	0.5 Hours
Total Time Outside Practical Recommended to Complete Practical	8.5 Hours
Assumed Knowledge[1]	No special requirements.
Workgroup Size	Groups of 3. (One of 4.)
Assessment	Submitted Report (See §2.1 for details) and Class Presentation
Submission Date	Wednesday, 2 May 2012 **before** 16:30
Submitted To	Ms Charlene Weimers (Administrative Officer) 3rd Floor E&E Building

2.1 Assessment

The practical will be assessed based on a printed report, submitted before the deadline. Please note that the report must be neatly presented. No hand-written work will be accepted. Communication skills form an integral part of any engineering task, and as such it will also be evaluated as an integral part of the report.

If it is deemed that the report, or the work it is reporting on, is not of high enough standard then the student will be requested to resubmit their report. Failure to obtain a pass grade for the report, and as such the practical, will result in an incomplete for the module as defined in the module framework.

The practical report will be returned to the student during class by the Monday after the submission date.

2.2 Venue

Students meet in the Auditorium (E203).

2.3 Teams

This practical is for groups of three (except group 6 which has four). Each group has to present a single report and presentation.

The teams, and team members, are listed below:

E-Mail	Surname	Group Number
[redacted]	[redacted]	4
[redacted]	[redacted]	3
[redacted]	[redacted]	6
[redacted]	[redacted]	3
[redacted]	[redacted]	6
[redacted]	[redacted]	6
[redacted]	[redacted]	5
[redacted]	[redacted]	4
[redacted]	[redacted]	5
[redacted]	[redacted]	1
[redacted]	[redacted]	2
[redacted]	[redacted]	2
[redacted]	[redacted]	1
[redacted]	[redacted]	5
[redacted]	[redacted]	1
[redacted]	[redacted]	2
[redacted]	[redacted]	3
[redacted]	[redacted]	6
[redacted]	[redacted]	4

[1] It is assumed that the student has the following knowledge. If the student falls short of this requirement then it is their responsibility to ensure that they study up on this material before the practical.

2.4 Report Submission

In addition to submitting the report in print, you also have to submit your presentation on a CD-ROM attached to the project report or e-mail a copy of the presentation to [redacted] before the deadline. The presentation filename must be:

ES414_Prac3_Presentation_Group#.pptx

2.5 Presentation

You must be prepared to present during any class after the submission date. Your presentation will be shown on the lecturer's laptop from the file you submitted, so you do not have to have your presentation with you at all times, just your presentation notes.

3 Resources

3.1 Required Reading

It is required of each student to ensure that they are familiar with the concepts discussed during class, as well as the material presented in chapter 9 of *Renewable and Efficient Electric Power Systems* by *Gilbert M. Masters*.

3.2 Preparation Required

The student must bring to the practical:

- *Renewable and Efficient Electric Power Systems* by *Gilbert M. Masters*
- Any class notes based on the work from Chapter 9 in *Masters*.
- Scientific Calculator
- Pen-and-paper for drawing and writing

Part 2: Content

4 Overview of Practical Structure

During this practical you, and your team, are responsible for designing your own learning path, based on the methodology and structures used in the previous two practicals. As an engineer it is not enough to just know the work taught to you, but also to be able to assimilate new knowledge areas quickly and effectively.

4.1 Why do this now?

Simple, the work presented in chapter 9 of Masters's *Renewable and Efficient Electric Power Systems* is a very broad overview at best. The solar resource is a complex system, but as you would have seen, a very well understood and predictable system. The photovoltaic conversion technology is also varied, with quite complex physics – but this too has been well described and modelled. But photovoltaic systems are a group name for a vast field of systems that cannot be modelled and analysed so simply; there are simply too many variations.

So Masters start by providing a broad categorization:

- Grid-Connected PV Systems
- Direct Load PV Systems
- Stand-Alone PV Systems

This is decent categorization as it very clearly separates our systems using a single parameter: *How the load is connected to the PV modules.*

So in essence our study of Photovoltaic Systems is a study of the loads that are linked to it. Since there are so many load types, and various load combinations, this practical forms the perfect opportunity for you to develop your own structure and understanding of <u>how</u> to study this work, rather than just a single set of examples which would not be able to even scratch the surface.

4.2 Assignment (And a bit of backstory)

You are working as a junior engineer for a small[2], but successful, engineering company that designs advanced sprinkler technologies. On the staff meeting on Tuesday afternoon the company's director, your boss, announces that she is interested in venturing into the solar photovoltaic energy market. She has read numerous articles about the market potential in Creamer Media's Engineering News as well as in various subject specific trade magazines.

However, before she goes further, she has to be sure that everybody knows what they are signing up for. Unfortunately this is a very busy time and the team is busy closing various projects. But, since your project has finished on time and you are the newest Electrical Energy Engineer (with a specialisation in Renewable Energy Systems) she asks if you, and your two team members, would pave the way for the rest of the team.

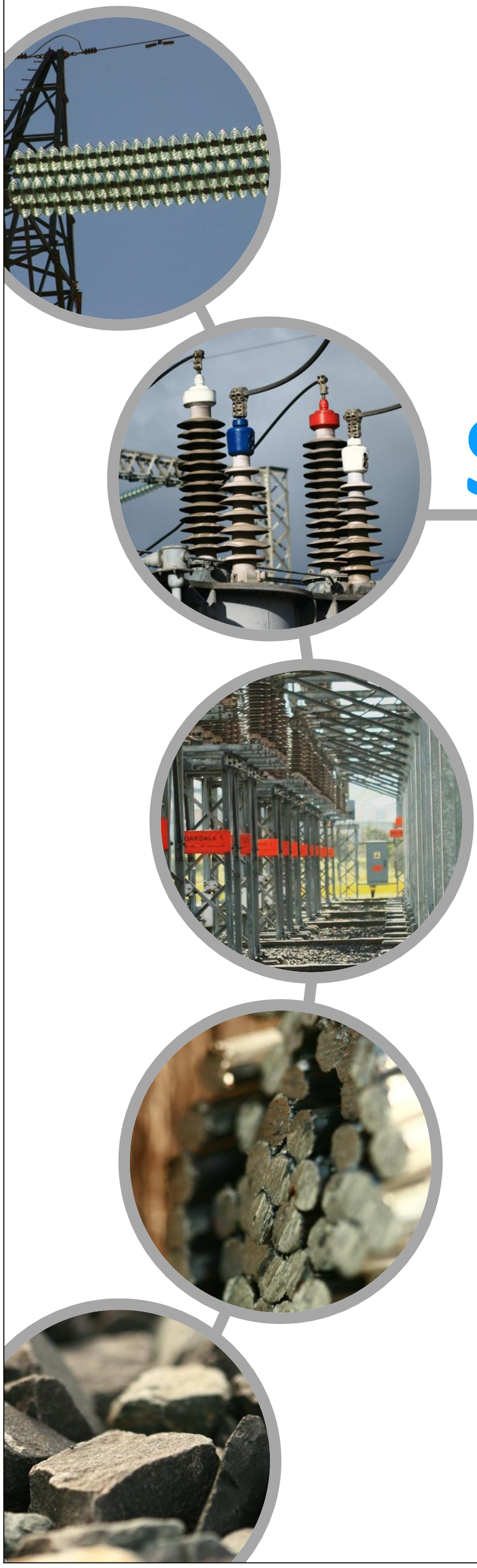
Your assignment is to make a detailed study of the various PV systems, ensuring that you understand each of the systems, how to use it, when to use it, what the advantages and disadvantages are. You have to write a thorough manual that can be used by the rest of the team when they have to migrate to this technology, so you have to ensure that you include a structure that they can use to

[2] You are part of a team of 30 people, support and janitorial staff included.

understand this work, as well as provide them with correct descriptions of the various systems, and us enough and correct examples that will assist their learning.

You also have to prepare a 10 minute, professional and concise MS Power Point presentation that will introduce the entire team, including your boss, to the new technology. (The only available system is MS Power Point; no other formats will be accepted.)

A.1.4 Project (redacted copy)



Department of Electrical and Electronic Engineering

ENERGY SYSTEMS 414

Solar Project :: 2012

Title: **Design Project**

Date of Practical: 8 May 2012

Practical Starts: Not Applicable

Practical Venue: Not Applicable

***Author*:** Pieter C. Oosthuizen

***Contact Time*:** 0 h

***Self-Work Time*:** 12 h

Assessment Type: Report and Presentation

Stellenbosch University

Table of Contents

Part 1: Practical Information

1 Introduction

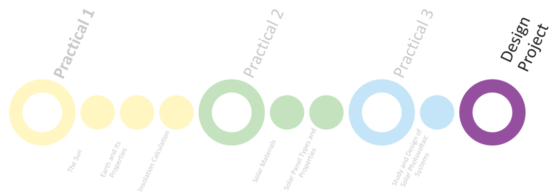
1.1 Project Overview

In this practical series we developed our knowledge of solar energy. The last step is to apply that knowledge to a simulated engineering project. In this project you will work in a group to analyse an engineering problem, make field measurements, calculate potential options, design the best system, and clearly and thoroughly report that design back to the client.

Particular attention must be paid to not only the design, but specifically the way in which you are able to communicate that design to your customer. It is crucial that you turn in a professional report.

1.2 Practical Series

This project is the final part of the Renewable Solar Energy Practical Set. The path is outlined below:



As you know by now each practical helped you to develop a set of tools, and supported your learning of a skill set regarding solar energy systems. In this project you should use all these tools to your maximum benefit.

A word of warning: You developed a substantial toolkit, and subsequently you are able to do quite a lot with it. However not everything is required for every project. Use the tools that are right for your project, and provide only the information that really makes an impact on the client's project.

Do not include information just because you have the tool for it. For example: No client, unless they are into space exploration, will really be interested in the distance from the earth to the sun at any given time – if you include this you are padding your report and you will be penalised for it.

2 Practical Properties

Property	Value
Date of Practical	8 May 2012
Practical Time Slot	Not Applicable
Practical Location	Not Applicable
Practical Contact Session Duration	0 Hours
Total Time Outside Practical Recommended to Complete Practical	12 Hours
Assumed Knowledge[1]	No special requirements.
Workgroup Size	Groups of 3. (One of 4.)
Assessment	Submitted Report (See §2.1 for details) and Class Presentation
Submission Date	Wednesday, 16 May 2012 **before** 12:00
Submitted To	Ms Charlene Weimers (Administrative Officer) 3rd Floor E&E Building

2.1 Assessment

The project will be assessed based on a printed report, submitted before the deadline. Please note that the report must be neatly presented. No hand-written work will be accepted. Communication skills form an integral part of any engineering task, and as such it will also be evaluated as an integral part of the report.

If it is deemed that the report, or the work it is reporting on, is not of high enough standard then the student will be requested to resubmit their report. Failure to obtain a pass grade for the report, and as such the project, will result in an incomplete for the module as defined in the module framework.

2.2 Venue

Students work on their own time.

2.3 Teams

This practical is for groups of three (except group 6 which has four). Each group has to present a single report and presentation.

The teams, and team members, are listed below:

E-Mail	Surname	Group Number
[redacted]	[redacted]	1
[redacted]	[redacted]	1
[redacted]	[redacted]	1
[redacted]	[redacted]	2
[redacted]	[redacted]	2
[redacted]	[redacted]	2
[redacted]	[redacted]	3

[1] It is assumed that the student has the following knowledge. If the student falls short of this requirement then it is their responsibility to ensure that they study up on this material before the practical.

[redacted]	[redacted]	3
[redacted]	[redacted]	3
[redacted]	[redacted]	4
[redacted]	[redacted]	4
[redacted]	[redacted]	4
[redacted]	[redacted]	5
[redacted]	[redacted]	5
[redacted]	[redacted]	5
[redacted]	[redacted]	6
[redacted]	[redacted]	6
[redacted]	[redacted]	6
[redacted]	[redacted]	6

2.4 Report Submission

In addition to submitting the report in print, you also have to submit your presentation via e-mail to [redacted] before the deadline. The presentation filename <u>must</u> be:

ES414_Project_Presentation_Group#.pptx

3 Resources

3.1 Required Reading

It is required of each student to ensure that they are familiar with the concepts discussed during class, as well as the material presented in chapters 7, 8 and 9 of *Renewable and Efficient Electric Power Systems* by *Gilbert M. Masters*.

3.2 Preparation Required

Preparation for the practical is at the discretion of the student.

Part 2: Content

4 Project for Group 1: Solar Power for US Central Library

The management of the JS Gericke Library at Stellenbosch University has expressed interest in a new renewable energy solution. Currently the library is open throughout the day, and uses a substantial amount of power. Library management would like to investigate the option of installing solar panels to offset some of this cost.

Design a grid-connected, no battery backup, solar energy system that is able to run the library, or at least offset the current energy usage substantially. Furthermore calculate the cost of such a system, and provide the library with an estimated ROI date calculated by using the savings on current electricity as the income factor.

Also, please note that you may not install anything on the Red Plain itself. You must use the rooftops of the adjacent buildings.

You must also submit a 10 minute presentation to introduce the project to the management team.

5 Project for Group 2: Solar Powered FIRGA

The computer user's area of the Faculty of Engineering, FIRGA, at Stellenbosch University has expressed interest in a power backup solution considering all the power outages. While investigating their options they happened upon solar energy systems and are curious as to whether this will solve their problems.

You must design a battery-backup system able to supply power to FIRGA for 3 hours. Furthermore you must design a solar panel set that can be used to charge the batteries as well as supply power to FIRGA during the day – when the sun is still shining and the batteries are already at capacity.

You can use the rooftops of the engineering building for the installed solar panels. The approximate dimensions and weight of the batteries must be provided so that the civil engineers can ensure the ground floor (where the batteries will be installed) has enough load carrying capacity.

You must also submit a 10 minute presentation to introduce the project to the management team.

6 Project for Group 3: Water Pumping for Coetzenburg

The Coetzenburg Sporting Ground's management want to find an alternative solution to their current grid-connected pumping scheme.

Design a pumping scheme to be installed at:

Longitude	Latitude
18°52'51.12"E	33°56'19.50"S

Figure 1: Coetzenburg Grounds Allocated Space for Solar Panel Installation (4500m^2)

The total allotted area, Figure 1, is 4500 m^2. You may install on the area indicated. (There is a lot of foliage. I recommend a field trip.)

Your system needs to be able to pump 28500 litres of water from the borehole per hour for 6 hours each day.

You must also submit a 10 minute presentation to introduce the project to the management team.

7 Project for Group 4: Power for the Botanical Gardens

The management of the botanical gardens want to install a solar energy system to power the borehole pump as well as charge the batteries to power the forty 35W LED nightlights that they use.

Design a system that will be able to supply them with the backup power required as well as a borehole pump that is able to pump 1000 litres per hour for 4 hours each day.

You have to be very careful not to disturb the ecosystem of the gardens. You are allowed to use the roof of the Old Conservatorium building for the panels.

You must also submit a 10 minute presentation to introduce the project to the management team.

8 Project for Group 5: Nightlight for Music Department

The Conservatorium of Music, on the corner of Victoria Street and Neethling Street is home to the Music Department of Stellenbosch University. The buildings, specifically the Endler Concert Hall are a campus icon, and hosts many great events each year.

The director of the conservatorium is interested in installing a solar power solution to offset the energy used by the twenty 500 Watt floodlights currently running outside, as well as potentially installing an additional twenty to increase safety around the building. Design a system that will be able to support their needs.

Ensure that you provide the director with an estimated ROI date calculated by using the savings that they would incur as opposed to running the system off the grid.

You must also submit a 10 minute presentation to introduce the project to the management team.

9 Project for Group 6: Solar Power for Exam Hall

The Engineering Faculty would like to create a solar powered exam hall. They have identified the Reitz Hall at the faculty and would like to know what the possibilities are. They are prepared to retrofit as needed.

The solar panel system must be able to power the exam room, as well as provide 4 hours of backup power. (So that power outages do not interfere with the students writing exams.)

Ensure that you provide the director with an estimated ROI date calculated by using the savings that they would incur as opposed to running the system off the grid. Also compare the results to the alternative of installing and running a generator.

You must also submit a 10 minute presentation to introduce the project to the management team.

Appendix B

Ethical Clearance

B.1 PCO-M-201304-KA-S-1

Assessment of Student Feedback on Modules to ascertain the worth of the feedback in measuring the effectiveness and impact of Practicals in Engineering Education.

The students are given a standard feedback form by the Centre for Teaching and Learning at the end of each module. This information is supposed to provide feedback to staff concerning the module in order to make improvements. But, this is a standard form that is provided to all faculties across the university. The question is whether this is sufficient to allow analysis of our specialised modules, with specific emphasis on the practicals. This will also allow us to compare the results from the CTL feedback with the custom surveys and interviews.

B.2 PCO-M-201304-OP-I-1

Assessment of Staff Perceptions regarding the role of practicals in engineering education: Staff of the Department of Electrical and Electronic Engineering(Interviews)

The equipment being developed during this project focusses on improving the practical education offering for Electrical Engineering. However, in order to design the best possible equipment, and to ultimately assess the effectiveness of that equipment, we need to understand the current practical offering.

Interviews with staff must be conducted to obtain their perspective regarding the role of practicals in engineering education. The interviews are free-form, focussing on the central theme of practicals in engineering education. However, the staff can expand the interview to any topic that they feel are applicable to the question. The moderator will attempt to keep the conversation on the general tone, without snubbing certain key information. This is an opportunity to assess the perceptions and not only compare them to each other, and to what is required from practicals, but also look at the difference between the staff and student opinions. These opinions are critical for the development of usable equipment for practical education.

B.3 PCO-M-201304-OP-IO-1

Assessment of Student Perceptions regarding Practicals in Engineering Education: Final Year Electrical and Electronic Group (Interviews)

The equipment being developed during this project focusses on improving the practical education offering for Electrical Engineering. However, in order to design the best possible equipment, and to ultimately assess the effectiveness of that equipment, we need to understand the current practical offering.

This particular study focusses on the perceptions and experiences that students have with practicals and tutorials. Since the first iteration of the equipment focusses on the work covered in the final year Renewable Energy Systems module at the Department of Electrical and Electronic Engineering, we have chosen to focus the study here as well. We will be taking a look at the current practical offering with the students currently enrolled in that specific module.

B.4 PCO-M-201304-OP-IO-2

Assessment of Practicals (Observations)

The equipment being developed during this project focusses on improving the practical education offering for Electrical Engineering. However, in order to design the best possible equipment, and to ultimately assess the effectiveness of that equipment, we need to understand the current practical offering.

This particular study focusses on the perceptions and experiences that students have with practicals and tutorials. In order to study this, we will be observing four (4) practical and four (4) tutorial sessions, for modules housed at the Department of Electrical and Electronic Engineering. The information gathered will allow researchers to correlate their findings of the practical experience as gathered from students in the Energy System 414 module.

B.5 PCO-M-201304-SE-O-1

Assessment of New Practical Equipment (Observations)

This is a study of the usability and function of the new equipment developed by this project. The equipment will be set up and the various parties will perform a practical element on the new and on the old equipment. The users will be observed, and the observations analysed and integrated into the design. This will be performed on multiple occasions as the equipment progresses in order to construct the best equipment.

B.6 The Application Documents

In this section we present one of the submitted applications, PCO-M-201304-KA-S-1 (§B.6.1), as an example of the requirements and format. However, we do advise that researches obtain the updated rules and regulations regarding such studies from the relevant authorities. We also include the letter granting institutional permission from Stellenbosch University. (§B.6.2)

B.6.1 PCO-M-201304-KA-S-1

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RESEARCH ETHICS COMMITTEE: HUMAN RESEARCH (HUMANIORA)

ETHICS COMMITTEE APPLICATION FORM

Application to the University of Stellenbosch RESEARCH ETHICS COMMITTEE: HUMAN RESEARCH (HUMANIORA)
for clearance of new/revised research projects

Name: Mr Pieter Cornelius Oosthuizen

Position/Professional Status: Post-Graduate (Master) Student

Study Code (Assigned by Researcher): PCO/M/201304/KA/S/1

Affiliation: Research Programme/Institution/Department:
Faculty of Engineering
Department of Electrical and Electronic Engineering
Electrical Energy Research Group

Please indicate (√) if you are a registered student at SU?

YES	√
NO	

If yes, for which degree/programme are you registered? Master of Science in Engineering (Electrical Engineering) – MScEng (Electrical)

Please specify the relevant Department at SU: Department of Electrical and Electronic Engineering

Who is your supervisor? Mr Johann M. Strauss

Your telephone and extension no. No: [redacted]
Supervisor's office extension no. Ext: [redacted]

E-Mail: [redacted]

Title of research project: (*Do not use abbreviations*)
The development of a solar energy practical learning environment for a senior module in Renewable Energy Systems

Where will the research be carried out?
At the Faculty of Engineering at Stellenbosch University

All the following sections must be completed (Please tick all relevant boxes where applicable)

1. **FUNDING OF THE RESEARCH: How will the research be funded?**
   No funding is required for this study.

2. **PURPOSE OF THE RESEARCH:**
   The purpose of the project at large is two-fold: firstly it is to design and develop a set of guidelines for the improved design and execution of engineering practicals, and secondly to put those design guidelines into place by developing a new set of practical equipment for the final year module on renewable and sustainable energy at the Department of Electrical and Electronic Engineering.

   In order to design a functional and effective solution it is vital that both the technical as well as the user challenges are addressed. As such a study of the perceptions and opinions of the staff, assistants and students of the engineering faculty with regard to practicals, and their role in engineering education must be assessed and studied. Furthermore, this study will help pave the way for future studies that will allow ever more detailed and continued assessment of our engineering education offering, thus promoting positive change and improvement.

   The proposal presented here is part of a set of studies aimed at analysing the aforementioned perceptions from multiple angles in an attempt to gain a more complete picture.

3. **AIMS AND OBJECTIVES OF THE RESEARCH:**
   - Assess the perspectives of staff with regards to practicals
   - Assess the perspectives of final year students with regards to practicals
   - Develop a set of guidelines for the design and execution of engineering practicals
   - Utilise these guidelines to develop a new practical teaching tool.

4. **SUMMARY OF THE RESEARCH**
   There are three main feedback mechanisms that we will study: surveys, interviews and Centre for Teaching and Learning module feedback. For this study we have selected a series of modules from first to final year, hosted by the Department of Electrical and Electronic Engineering, and we will be conducting interviews and surveys with those students, as well as looking at the CTL feedback for those modules for the last three years.

   By combining the three views we should be able to gain a proper insight into the current perceptions of practical and their role in engineering education.

Study Code: PCO/M/201304/KA/S/1 Page 2 of 7

5. NATURE AND REQUIREMENTS OF THE RESEARCH

5.1 How should the research be characterized ***(Please tick ALL appropriate boxes)***

5.1.1	Personal and social information collected directly from participants/subjects	-
5.1.2	Participants/subjects to undergo physical examination	-
5.1.3	Participants/subjects to undergo psychometric testing	-
5.1.4	Identifiable information to be collected about people from available records	-
5.1.5	Anonymous information to be collected from available records	√
5.1.6	Literature, documents or archival material to be collected on individuals/groups	-

5.2 Participant/Subject Information Sheet attached? (*for written and verbal consent)*

YES	
NO	√

5.3 Informed Consent form attached? *(for written consent)*

YES	
NO	√

5.3.1 If informed consent is not necessary, please state why: The information is retrieved directly from the Centre for Teaching and Learning. The data provided by them does not contain any identifiable information, and none of the staff information will be requested.

NB: If a questionnaire, interview schedule or observation schedule/framework for ethnographic study will be used in the research, it must be attached. The application cannot be considered if these documents are not included.

5.4 Will you be using any of the above mentioned measurement instruments in the research?

YES	
NO	√

6 PARTICIPANTS/SUBJECTS IN THE STUDY

6.1 If humans are being studied, state where they are selected:

No, not directly. Only records provided by Centre for Teaching and Learning will be used.

6.2 Please mark (√) the appropriate boxes:

Participants/subjects will:	YES	NO
be asked to volunteer	√	
be selected		√

6.2.1 State how the participants/subjects will be selected, and/or who will be asked to volunteer:

Students are asked to volunteer to complete the module feedback program.

6.2.2. Please mark (√) the appropriate boxes:

Participants/subjects are:	YES	NO
Will SU student, alumni or staff data be used in this research		√
Will interviews be conducted with SU student, alumni or staff		√
Will questionnaires be used and distributed on SU campuses		√
Will electronic questionnaires be placed on the SU website?		√

6.3 Are the participants/subjects subordinate to the person doing the recruiting?

YES	
NO	√

6.3.1 If yes, justify the selection of subordinate participants / subjects: N/A

6.4 Will control participants/subjects be used?

YES	
NO	√

6.4.1 If yes, explain how they will be selected: N/A

6.5 What records, if any, will be used, and how will they be accessed? Have you obtained formal permission to use these records?
The student feedback for the following modules will be retrieved from the Centre for Teaching and Learning:

- Energy Systems 414 (Year 2012)

6.6 What is the age range of the participants/subjects in the study? N/A

6.6.1 Was consent from guardians/parents obtained for participants/subjects 17 years and younger? N/A

~~*If YES, please attach the appropriate forms.*~~

If NO, please state why: N/A

6.7 Will participation or non-participation disadvantage the participants/subjects in any way?

YES	
NO	√

6.7.1 If yes, explain in what way: N/A

6.8 Will the research benefit the participants/subjects in any direct way?

YES	
NO	√

6.8.1 If yes, please explain in what way: N/A

7. PROCEDURES

7.1 Mark research procedure(s) that will be used:

Literature	
Documentary	
Personal records	
Interviews	
Survey	
Participant observation	
Other: Records from surveys conducted by the Centre for Teaching and Learning	√

The records requested for each subject will pertain only to the module itself, and not to the lecturer presenting the module. The student's marks for the module, as well as their comments will be studied.

7.2 How will the data be stored to keep it safe and prevent unauthorized access? What happens to the data on completion of the research?

This data from this study is stored online using a private Dropbox account. Dropbox uses a SSL and AES-256 bit encryption and uses the Amazon Simple Storage Service (S3) for its own storage requirements.

The data will be presented in the project and the raw data stores will be deleted upon completion of the project. Only the data as presented in the final thesis will remain.

7.3 If an interview form/schedule; questionnaire or observation schedule/framework will be used, is it attached?

YES	
NO	√

7.4 Risks of the procedure(s): Participants/subjects will/may suffer:

No risk	√
Discomfort	
Pain	
Possible complications	
Persecution	
Stigmatization	
Negative labelling	
Other (please specify)	

7.4.1 If you have checked any of the above except "no risk", please provide details:
N/A

8. RESEARCH PERIOD

(a) When will the research commence:
1 March 2013

(b) Over what approximate time period will the research be conducted:
Three (3) Weeks

9. GENERAL

9.1 Has permission of relevant authority(ies) been obtained?

YES	-
NO	√

9.1.1 If yes, state name/s of authority/ies:

The release of information from the Institutional Permission Department at Stellenbosch University has already been discussed. The same has been done with the Centre for Teaching and Learning. However, both organisations require that the ethical clearance be performed first.

9.2 Confidentiality: How will confidentiality be maintained to ensure that participants/subjects/patients/controls are not identifiable to persons not involved in the research?

The names of the students were never recorded. The names of the lecturers presenting the modules will also not be used. The emphasis of the research is people's perception of practicals, not of the people involved.

9.3 Results: To whom will results be made available, and how will the findings be reported to the research participants?

The processed results will be made available to the general public in the form of a thesis and possible article publications. The participants will be able to review the information when the thesis is published.

9.4 There will be financial costs to:

participant/subject	No
institution	No
Other (please specify)	No

9.4.1 Explain any box marked YES: N/A

9.5 Research proposal/protocol attached:

YES	√
NO	-

9.6 Any other information which may be of value to the Committee should be provided here:

This study forms part of a larger study within the authors MScEng research project which attempts to understand practicals and all the challenges involved for all relevant parties. As such this study is not the only factor that will influence the outcome of the project. However, the utmost care and consideration has been applied to the methodology, using the authors experience in teaching and learning, to construct a process that is as efficient and clear as possible in order to collect the data and ensure that the conclusions based on the data can be defended.

Please note that all the information provided to participants, for surveys, interviews or during observations, will also be provided in Afrikaans. The documents were not included here for the sake of brevity.

Date: 5 February 2013 **Applicant`s signature** [redacted]

Who will supervise the project?

Name: Mr Johann M. Strauss
Programme/Institution/Department: D[redacted]rical and Electronic Engineering

Date: 5 February 2013 **Signature:** [redacted]

Director/Head/Research Coordinator of Department/Institute in which study is conducted:

I declare that this research proposal has been approved by the relevant Department or Faculty and that it complies with acceptable scientific research standards.

Name: T. Jones.
Date: 14/02/2013 **Signature:** [redacted]

B.6.2 Institutional Permission

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jou kennisvennoot • your knowledge partner

20 February 2013

Mr Pieter C. Oosthuizen
Department of Electrical
and Electronic Engineering
Faculty of Engineering
Stellenbosch University

Dear Mr Oosthuizen

Research Project: ***The development of solar energy practical learning environment for a senior module in Renewable Energy Systems***

The researcher has institutional permission to solicit the participation of students and staff with the Department of Electrical and Electronic Engineering and to assess 2012 student feedback as compiled by the Centre for Teaching and Learning for the module, Energy Systems 414, as indicated in the research proposal of this research project.

In terms of SU policies student feedback is anonymous and may only be used for educational development purposes. Since this researcher is involved in the offering of the particular module, access to the completed student feedback forms is standard practice. Furthermore, the research project is deemed to be a particular form of educational development. Therefore permission is granted to use the information gained from the student feedback forms for this research.

The researcher is encouraged to seek opportunities to share his research results with his department and faculty in support of the on-going educational development activities in the department and faculty. The researcher is therefore requested to discuss the project with the Vice Dean (Teaching and QA) of the Faculty of Engineering.

Institutional permission is granted with the following conditions:

-all participation is voluntary,
-participants may withdraw at any time, without consequence,
-data that is collected may only be used for the purpose of this study,

Afdeling Institusionele Navorsing en Beplanning • Institutional Research and Planning Division
Privaatsak/Private Bag X1 • Stellenbosch • 7602 • Suid-Afrika/South Africa
Tel. +27 21 808 3967 • Faks/Fax +27 21 808 4533

-individuals may not be identified in the dissemination of the results of the study.

The researcher will act in accordance with Stellenbosch University's principles of research ethics and scientific integrity as stipulated in the *Framework Policy for the Assurance and Promotion of Ethically Accountable Research at Stellenbosch University.*

Best wishes,

[redacted]

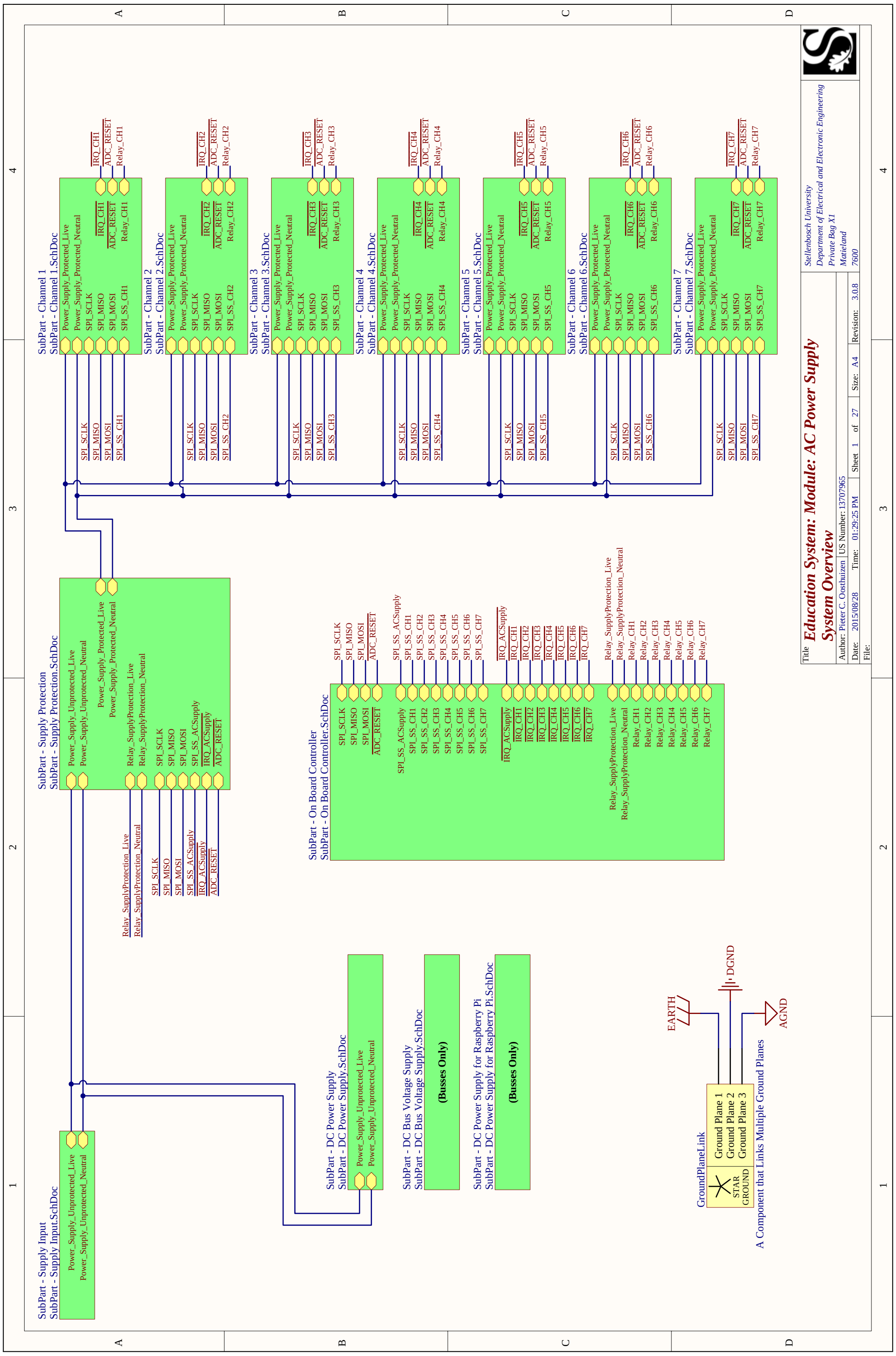
Jan Botha
Senior Director: Institutional Research and Planning

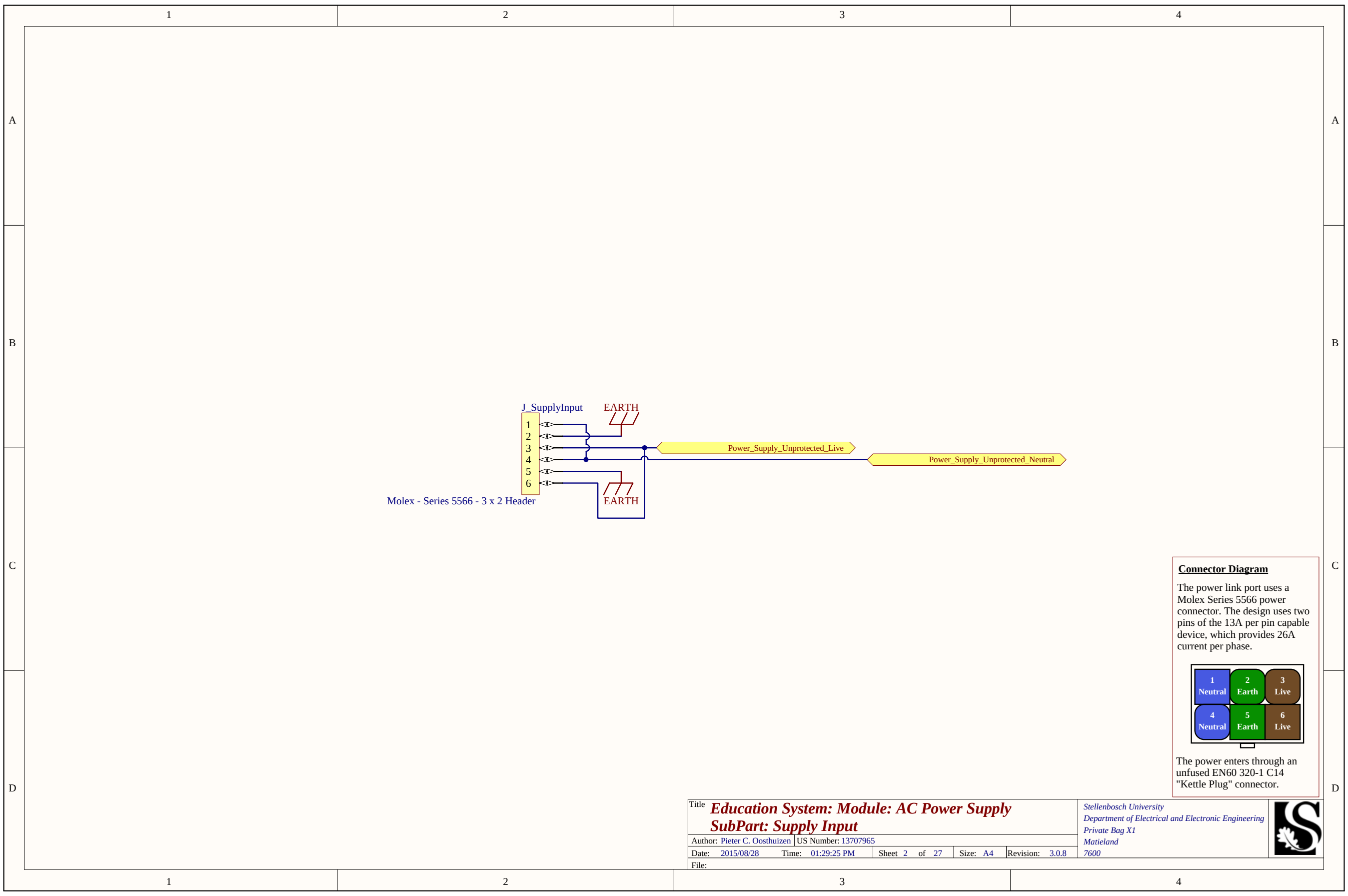
Afdeling Institusionele Navorsing en Beplanning • Institutional Research and Planning Division
Privaatsak/Private Bag X1 • Stellenbosch • 7602 • Suid-Afrika/South Africa
Tel. +27 21 808 3967 • Faks/Fax +27 21 808 4533

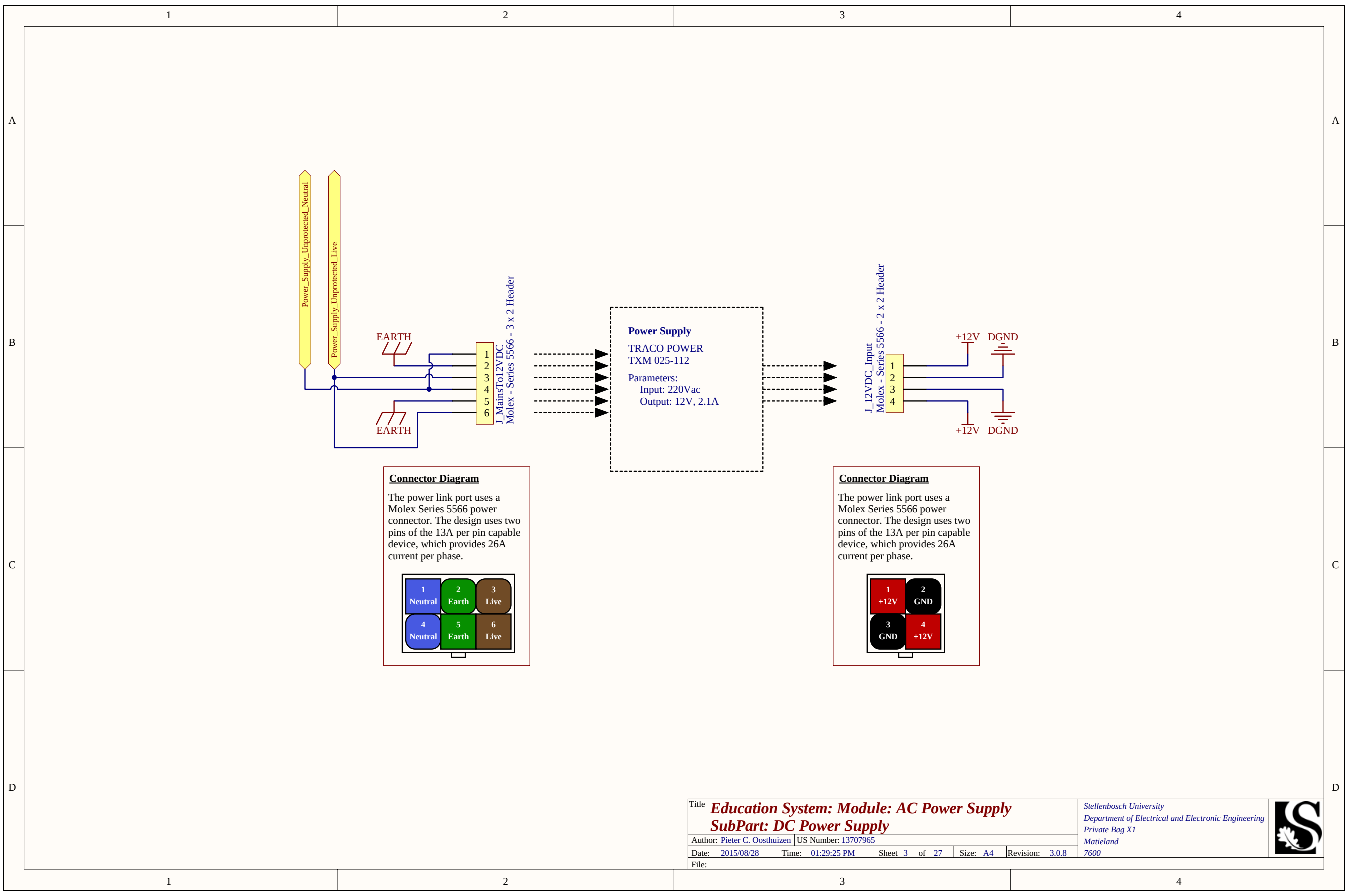
Appendix C

Circuit Diagrams

C.1 Prototype Three: AC Power Supply Module




J_SupplyInput
EARTH
Power_Supply_Unprotected_Live
Power_Supply_Unprotected_Neutral
Molex - Series 5566 - 3 x 2 Header
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
Education System: Module: AC Power Supply
SubPart: Supply Input
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28 Time: 01:29:25 PM Sheet 2 of 27 Size: A4 Revision: 3.0.8
Stellenbosch University
Department of Electrical and Electronic Engineering
Private Bag X1
Matieland
7600


Power_Supply_Unprotected_Neutral
Power_Supply_Unprotected_Live
EARTH
J_MainsTo12VDC
Molex - Series 5566 - 3 x 2 Header
Power Supply
TRACO POWER
TXM 025-112
Parameters:
Input: 220Vac
Output: 12V, 2.1A
J_12VDC_Input
Molex - Series 5566 - 2 x 2 Header
+12V
DGND
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
Education System: Module: AC Power Supply
SubPart: DC Power Supply
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28 Time: 01:29:25 PM Sheet 3 of 27 Size: A4 Revision: 3.0.8
Stellenbosch University
Department of Electrical and Electronic Engineering
Private Bag X1
Matieland
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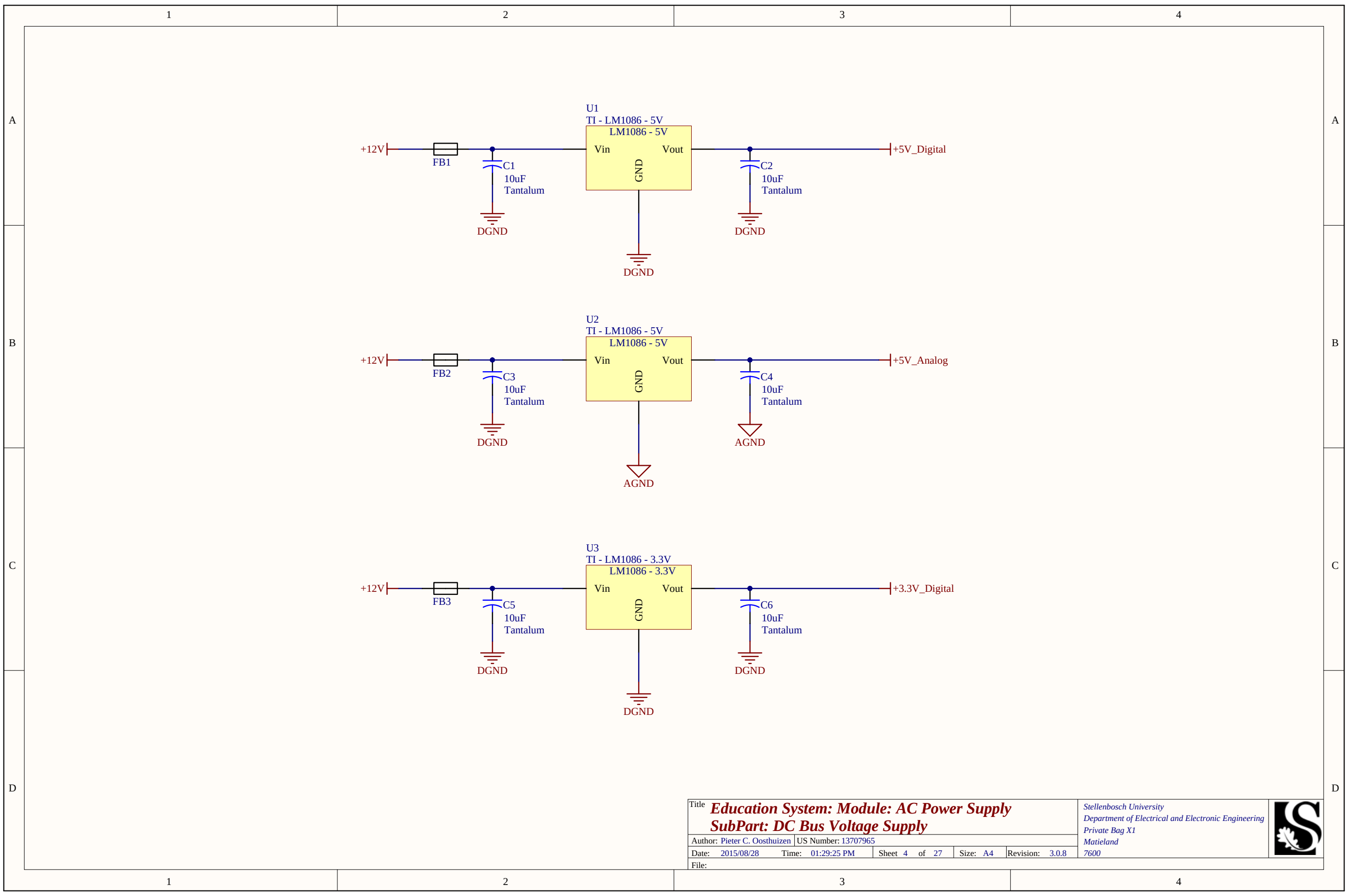
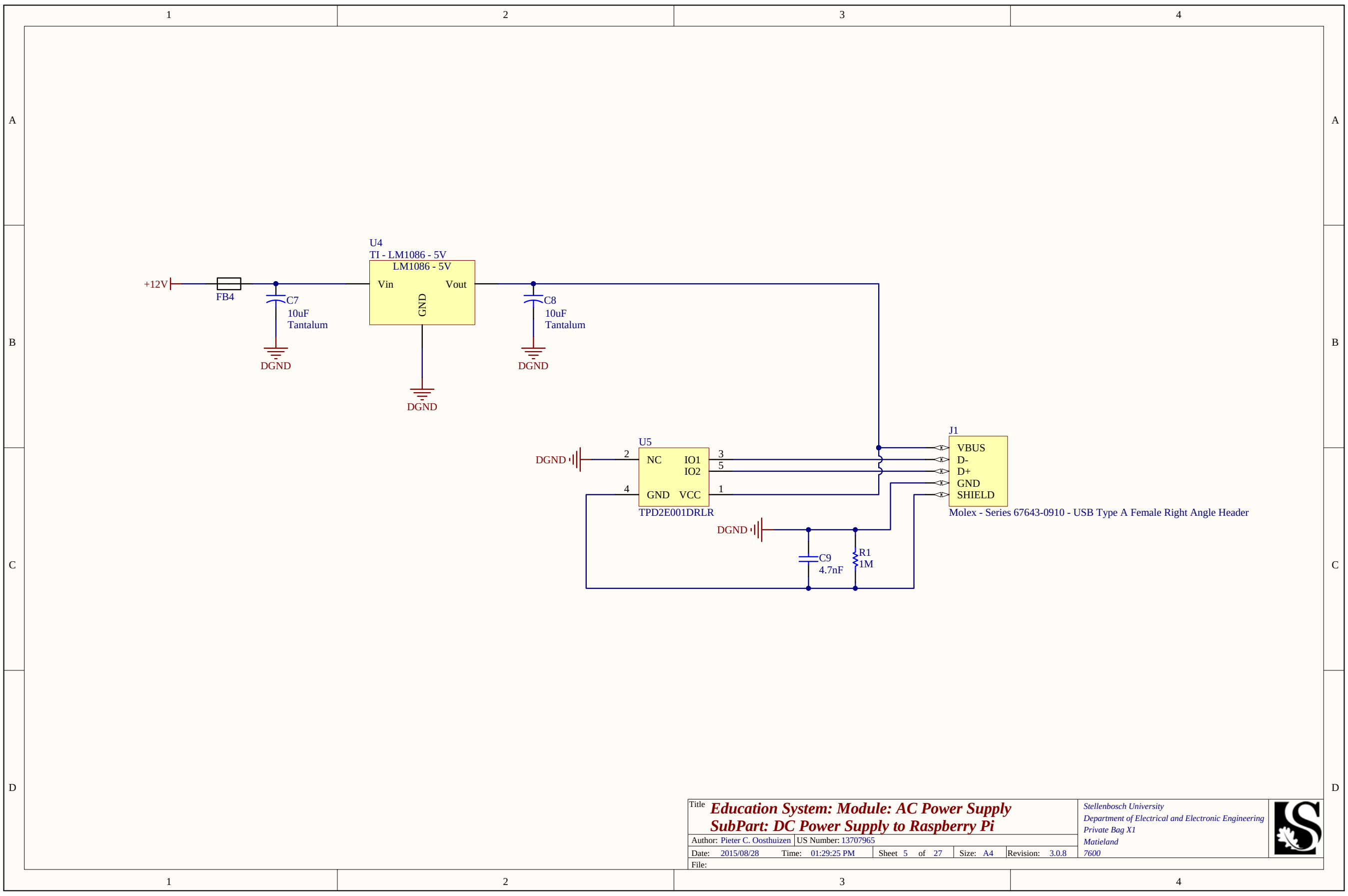

U1
TI - LM1086 - 5V
LM1086 - 5V
Vin
Vout
GND
+12V
FB1
C1
10uF
Tantalum
DGND
C2
10uF
Tantalum
+5V_Digital
U2
TI - LM1086 - 5V
LM1086 - 5V
FB2
C3
C4
AGND
+5V_Analog
U3
TI - LM1086 - 3.3V
LM1086 - 3.3V
FB3
C5
C6
+3.3V_Digital
Education System: Module: AC Power Supply
SubPart: DC Bus Voltage Supply
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:25 PM
Sheet 4 of 27
Size: A4
Revision: 3.0.8
Stellenbosch University
Department of Electrical and Electronic Engineering
Private Bag X1
Matieland
7600


U4
TI - LM1086 - 5V
LM1086 - 5V
Vin
Vout
GND
+12V
FB4
C7
10uF
Tantalum
DGND
C8
10uF
Tantalum
U5
NC
IO1
IO2
GND
VCC
TPD2E001DRLR
J1
VBUS
D-
D+
GND
SHIELD
Molex - Series 67643-0910 - USB Type A Female Right Angle Header
C9
4.7nF
R1
1M
Education System: Module: AC Power Supply
SubPart: DC Power Supply to Raspberry Pi
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:25 PM
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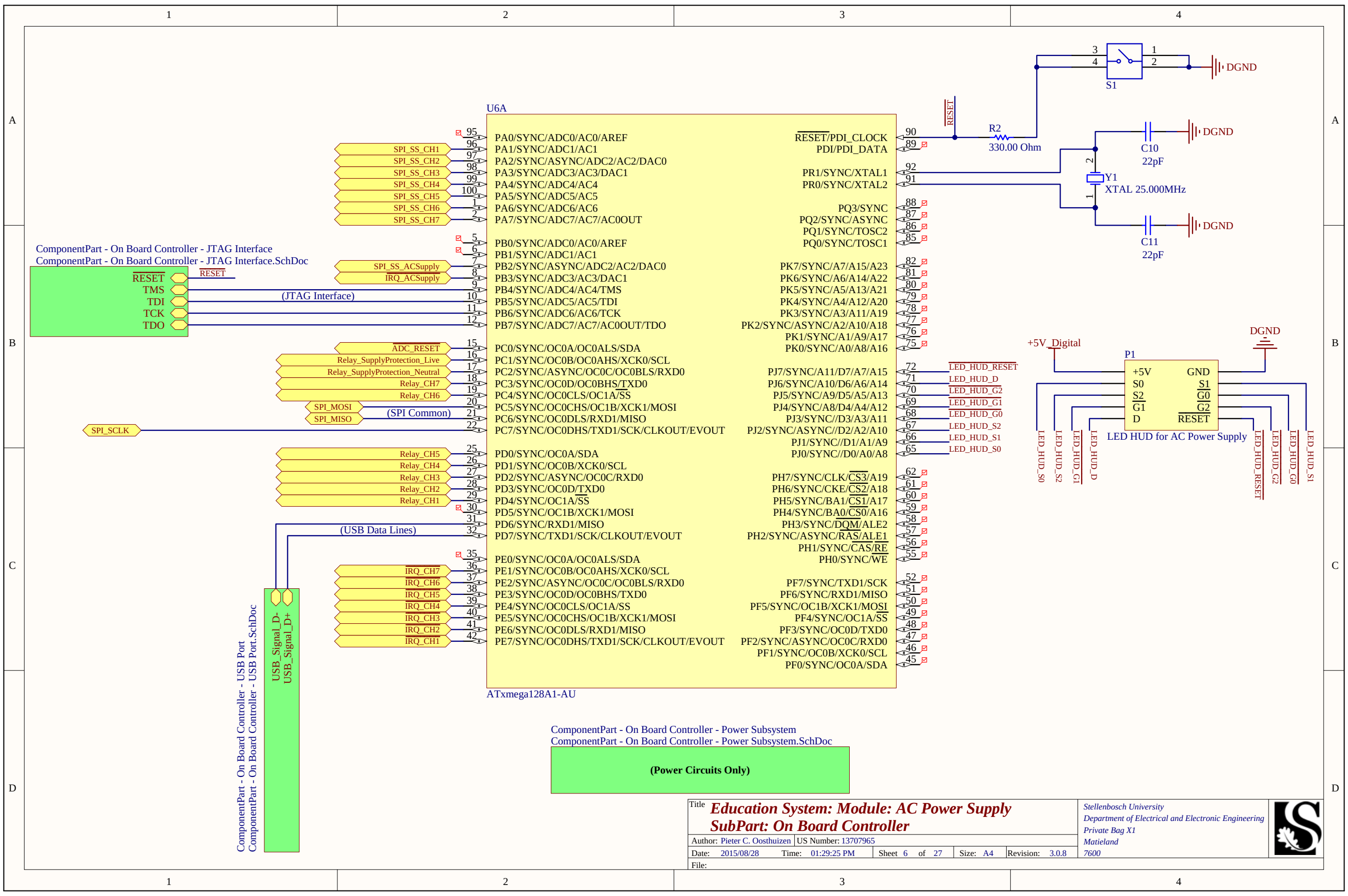
U6A
ATxmega128A1-AU
ComponentPart - On Board Controller - JTAG Interface
ComponentPart - On Board Controller - JTAG Interface.SchDoc
RESET
TMS
TDI
TCK
TDO
(JTAG Interface)
(SPI Common)
(USB Data Lines)
ComponentPart - On Board Controller - USB Port
ComponentPart - On Board Controller - USB Port.SchDoc
USB_Signal_D-
USB_Signal_D+
ComponentPart - On Board Controller - Power Subsystem
ComponentPart - On Board Controller - Power Subsystem.SchDoc
(Power Circuits Only)
S1
R2
330.00 Ohm
DGND
C10
22pF
Y1
XTAL 25.000MHz
C11
22pF
+5V_Digital
P1
LED HUD for AC Power Supply
Education System: Module: AC Power Supply
SubPart: On Board Controller
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
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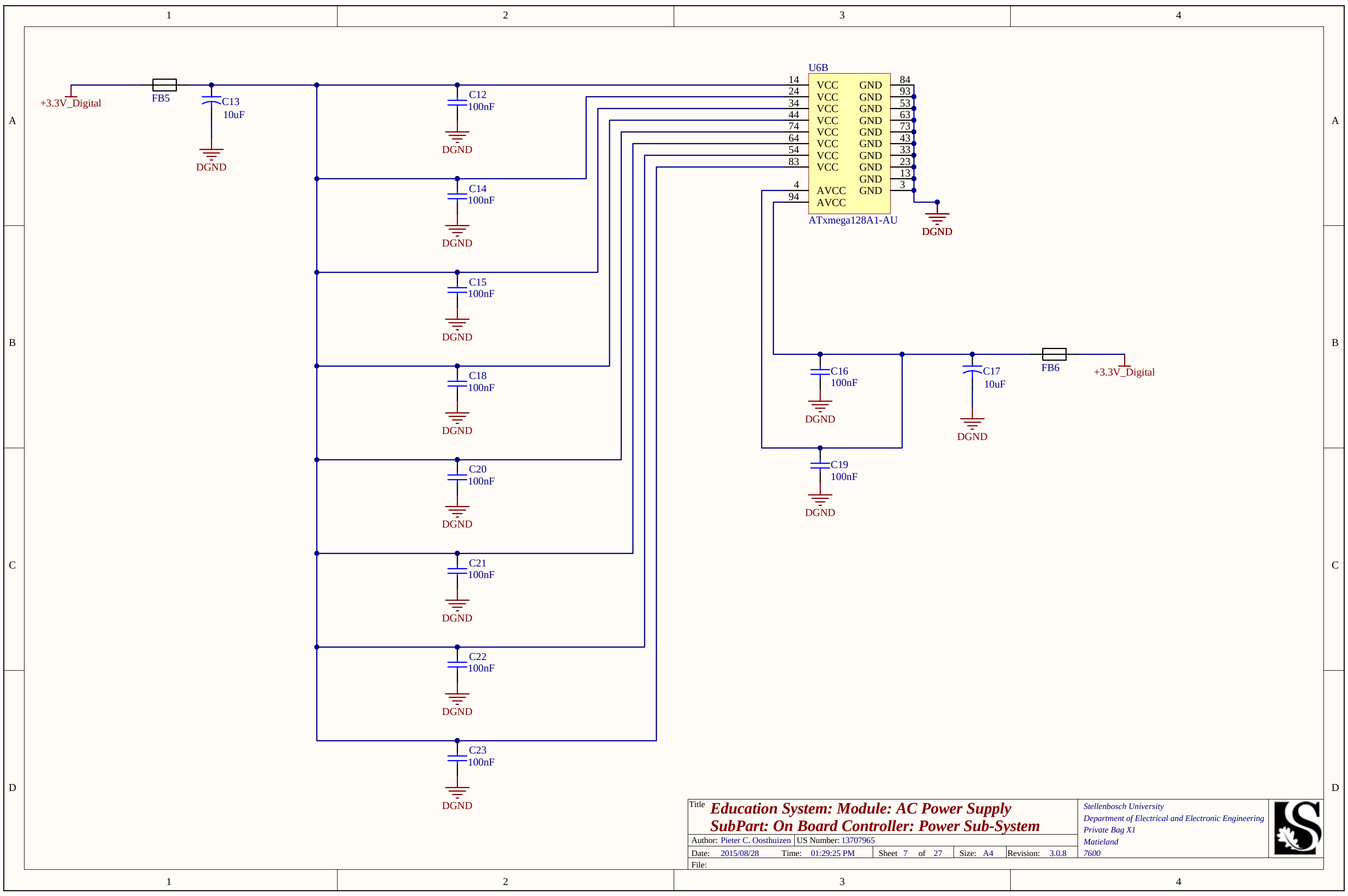
U6B
ATxmega128A1-AU
+3.3V_Digital
FB5
C13
10uF
C12
100nF
C14
100nF
C15
100nF
C18
100nF
C20
100nF
C21
100nF
C22
100nF
C23
100nF
C16
100nF
C17
10uF
C19
100nF
FB6
DGND
Education System: Module: AC Power Supply
SubPart: On Board Controller: Power Sub-System
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:25 PM
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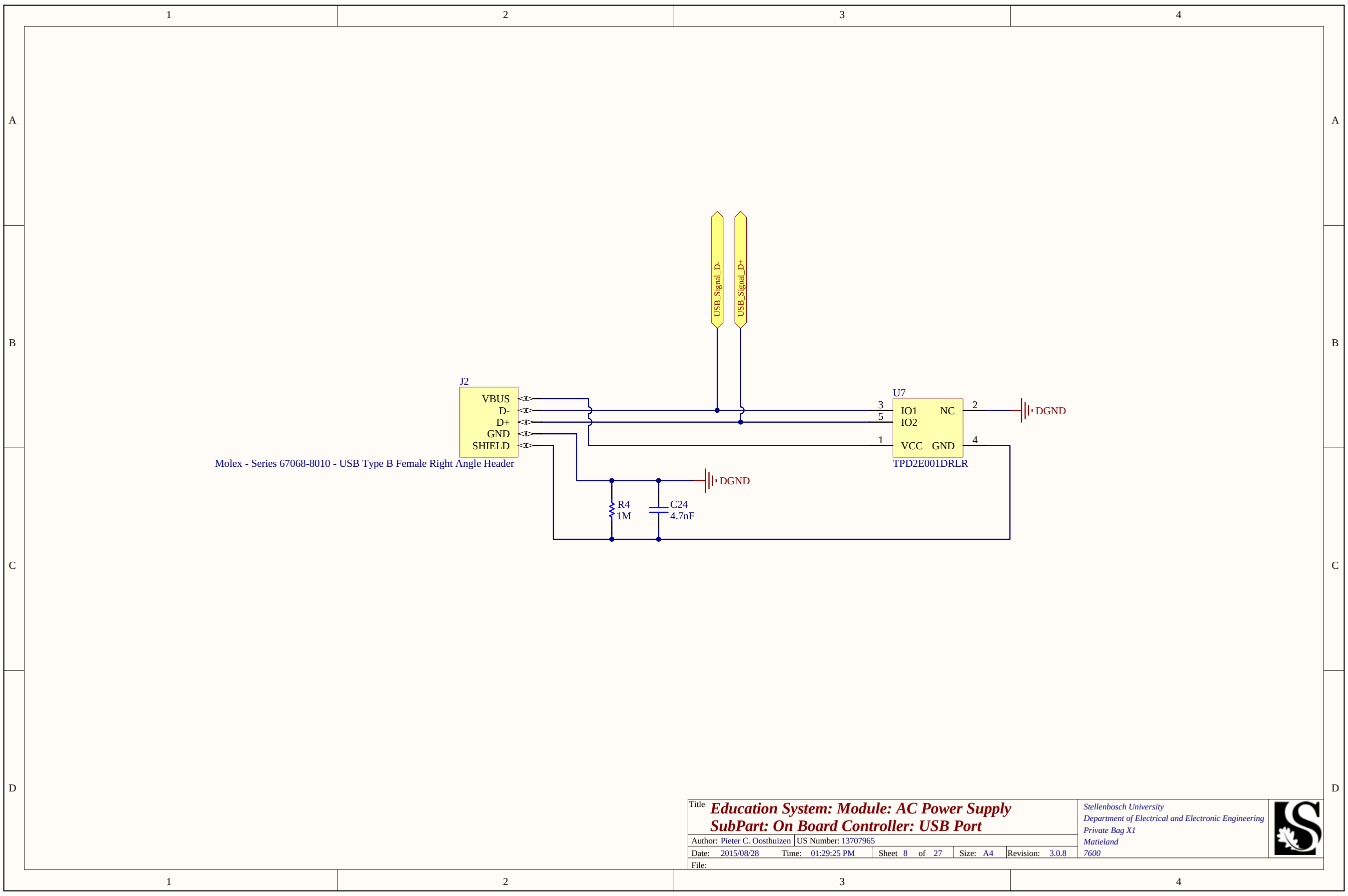

USB_Signal_D-
USB_Signal_D+
J2
VBUS
D-
D+
GND
SHIELD
Molex - Series 67068-8010 - USB Type B Female Right Angle Header
U7
IO1
IO2
NC
VCC
GND
TPD2E001DRLR
DGND
R4
1M
C24
4.7nF
Title
Education System: Module: AC Power Supply
SubPart: On Board Controller: USB Port
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
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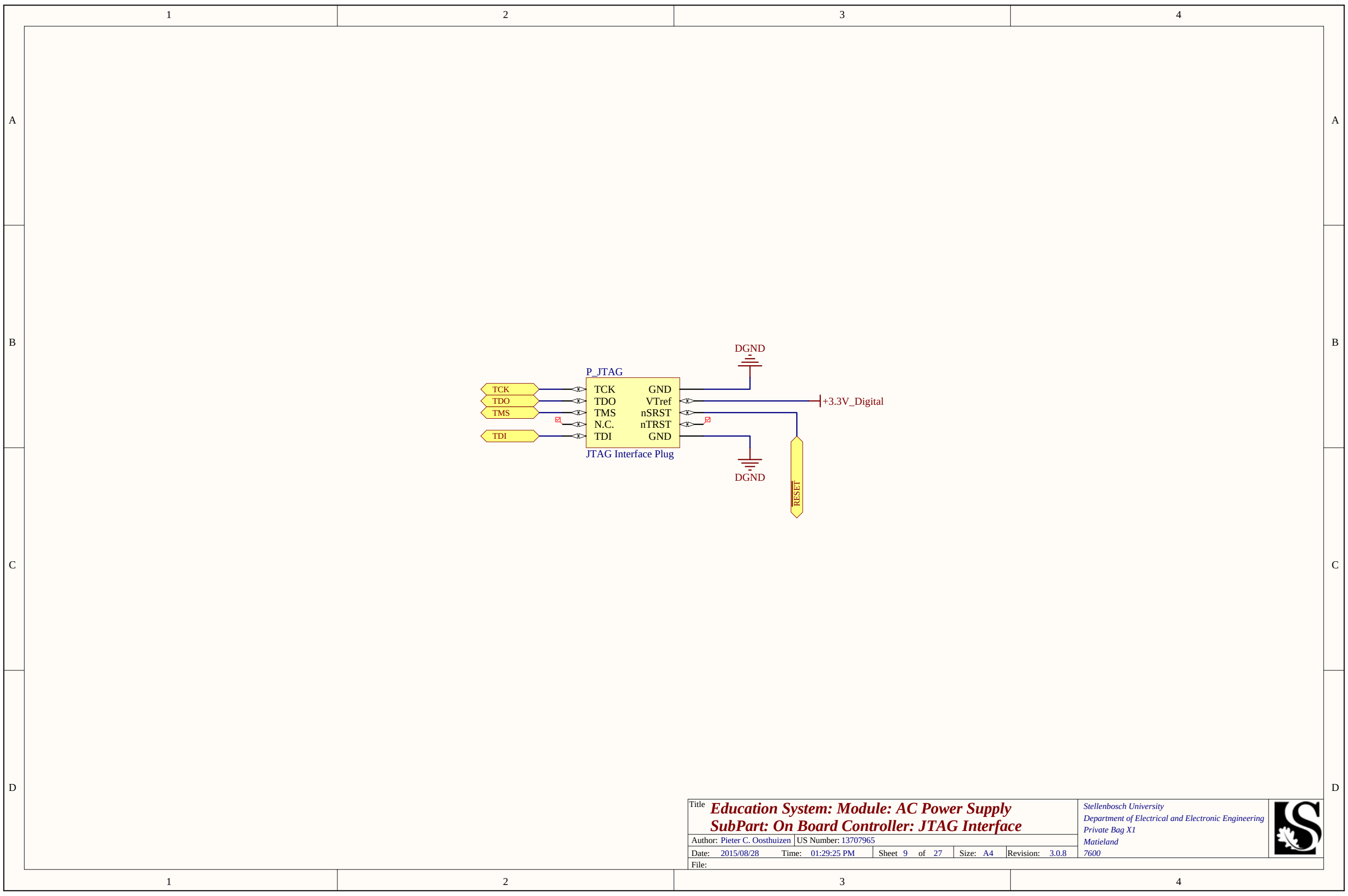

P_JTAG
TCK
TDO
TMS
TDI
N.C.
GND
VTref
nSRST
nTRST
JTAG Interface Plug
DGND
+3.3V_Digital
RESET
Title
Education System: Module: AC Power Supply
SubPart: On Board Controller: JTAG Interface
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
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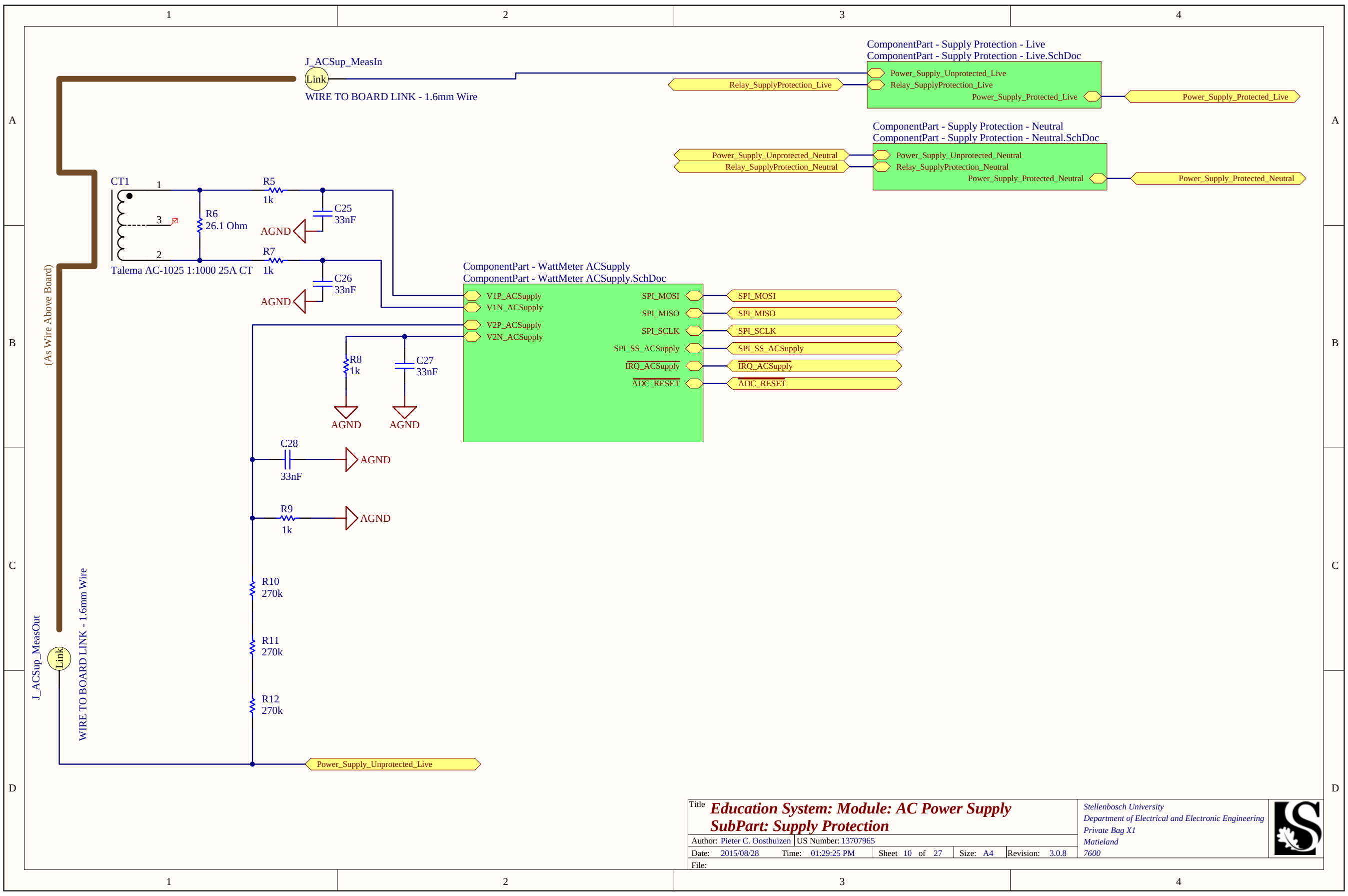
J_ACSup_MeasIn
Link
WIRE TO BOARD LINK - 1.6mm Wire
ComponentPart - Supply Protection - Live
ComponentPart - Supply Protection - Live.SchDoc
Power_Supply_Unprotected_Live
Relay_SupplyProtection_Live
Power_Supply_Protected_Live
ComponentPart - Supply Protection - Neutral
ComponentPart - Supply Protection - Neutral.SchDoc
Power_Supply_Unprotected_Neutral
Relay_SupplyProtection_Neutral
Power_Supply_Protected_Neutral
CT1
Talema AC-1025 1:1000 25A CT
R5 1k
R6 26.1 Ohm
R7 1k
C25 33nF
C26 33nF
AGND
ComponentPart - WattMeter ACSupply
ComponentPart - WattMeter ACSupply.SchDoc
V1P_ACSupply
V1N_ACSupply
V2P_ACSupply
V2N_ACSupply
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_ACSupply
IRQ_ACSupply
ADC_RESET
R8 1k
C27 33nF
C28 33nF
R9 1k
R10 270k
R11 270k
R12 270k
(As Wire Above Board)
J_ACSup_MeasOut
WIRE TO BOARD LINK - 1.6mm Wire
Power_Supply_Unprotected_Live
Title Education System: Module: AC Power Supply
SubPart: Supply Protection
Author: Pieter C. Oosthuizen US Number: 13707965
Date: 2015/08/28 Time: 01:29:25 PM Sheet 10 of 27 Size: A4 Revision: 3.0.8
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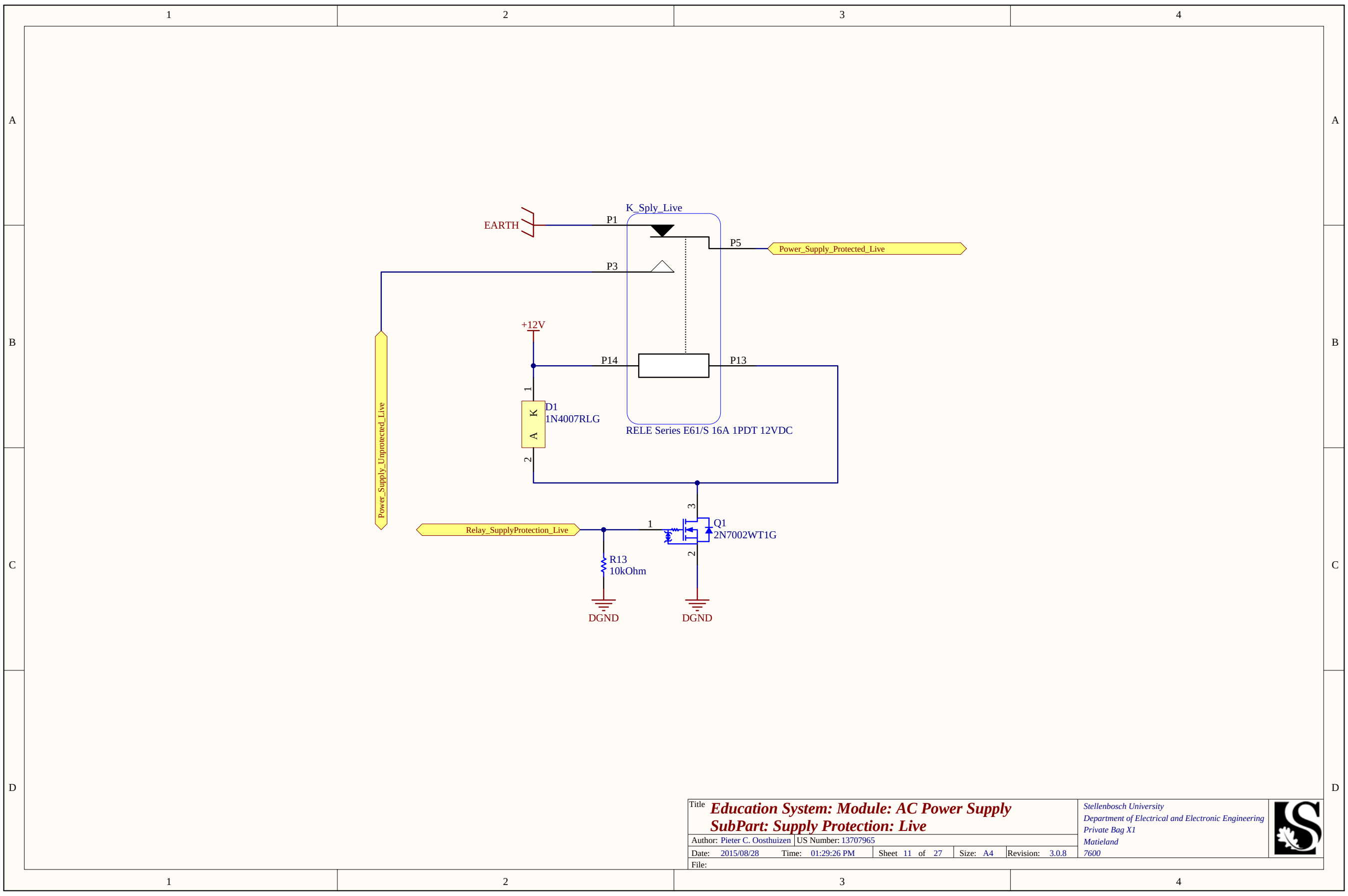
K_Sply_Live
EARTH
P1
P5
P3
Power_Supply_Protected_Live
+12V
P14
P13
D1 1N4007RLG
RELE Series E61/S 16A 1PDT 12VDC
Power_Supply_Unprotected_Live
Relay_SupplyProtection_Live
Q1 2N7002WT1G
R13 10kOhm
DGND
Title Education System: Module: AC Power Supply
SubPart: Supply Protection: Live
Author: Pieter C. Oosthuizen US Number: 13707965
Date: 2015/08/28 Time: 01:29:26 PM Sheet 11 of 27 Size: A4 Revision: 3.0.8
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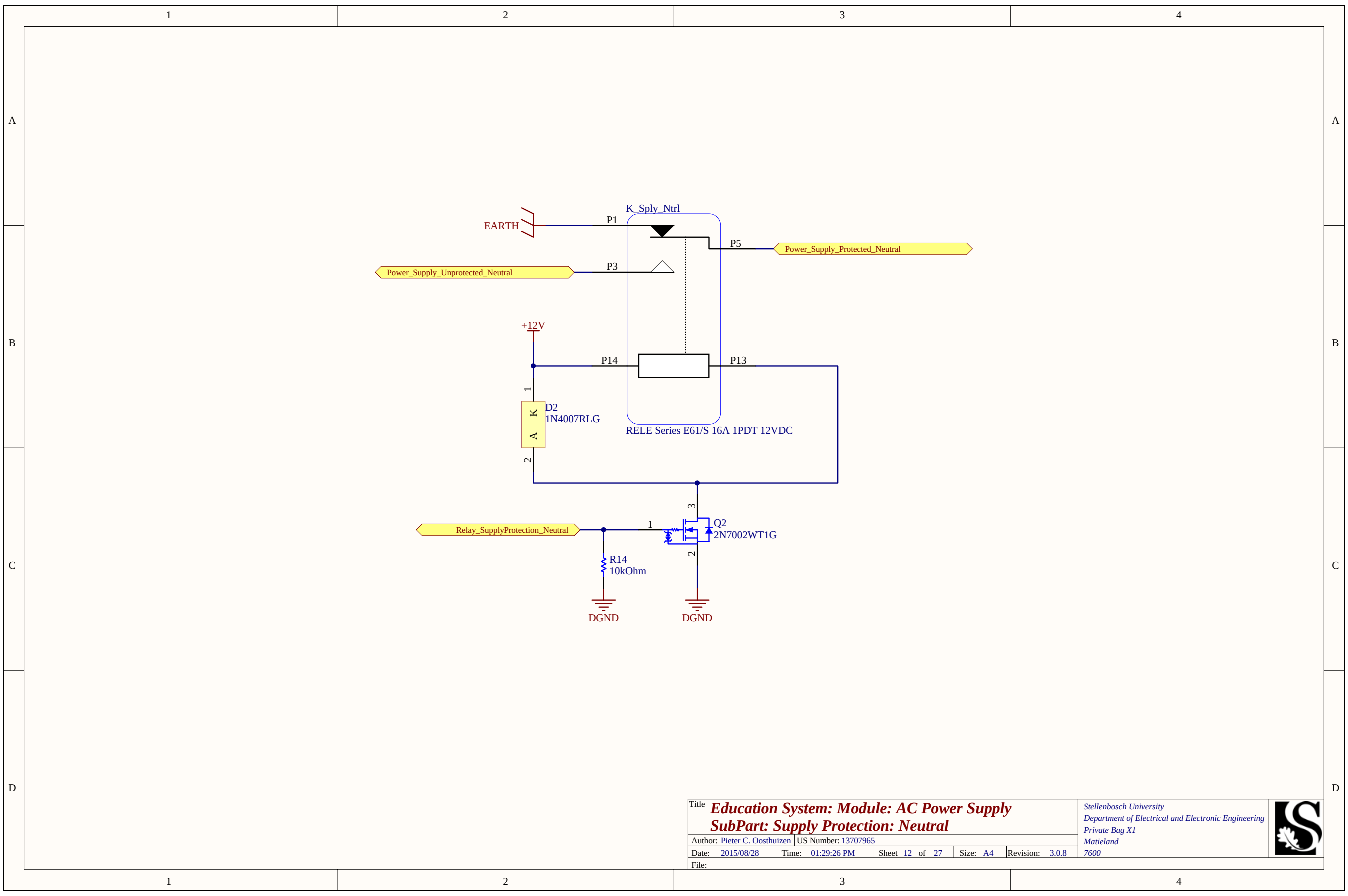
K_Sply_Ntrl
EARTH
P1
P5
P3
Power_Supply_Protected_Neutral
Power_Supply_Unprotected_Neutral
+12V
P14
P13
D2
1N4007RLG
RELE Series E61/S 16A 1PDT 12VDC
Relay_SupplyProtection_Neutral
Q2
2N7002WT1G
R14
10kOhm
DGND
DGND
Education System: Module: AC Power Supply
SubPart: Supply Protection: Neutral
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
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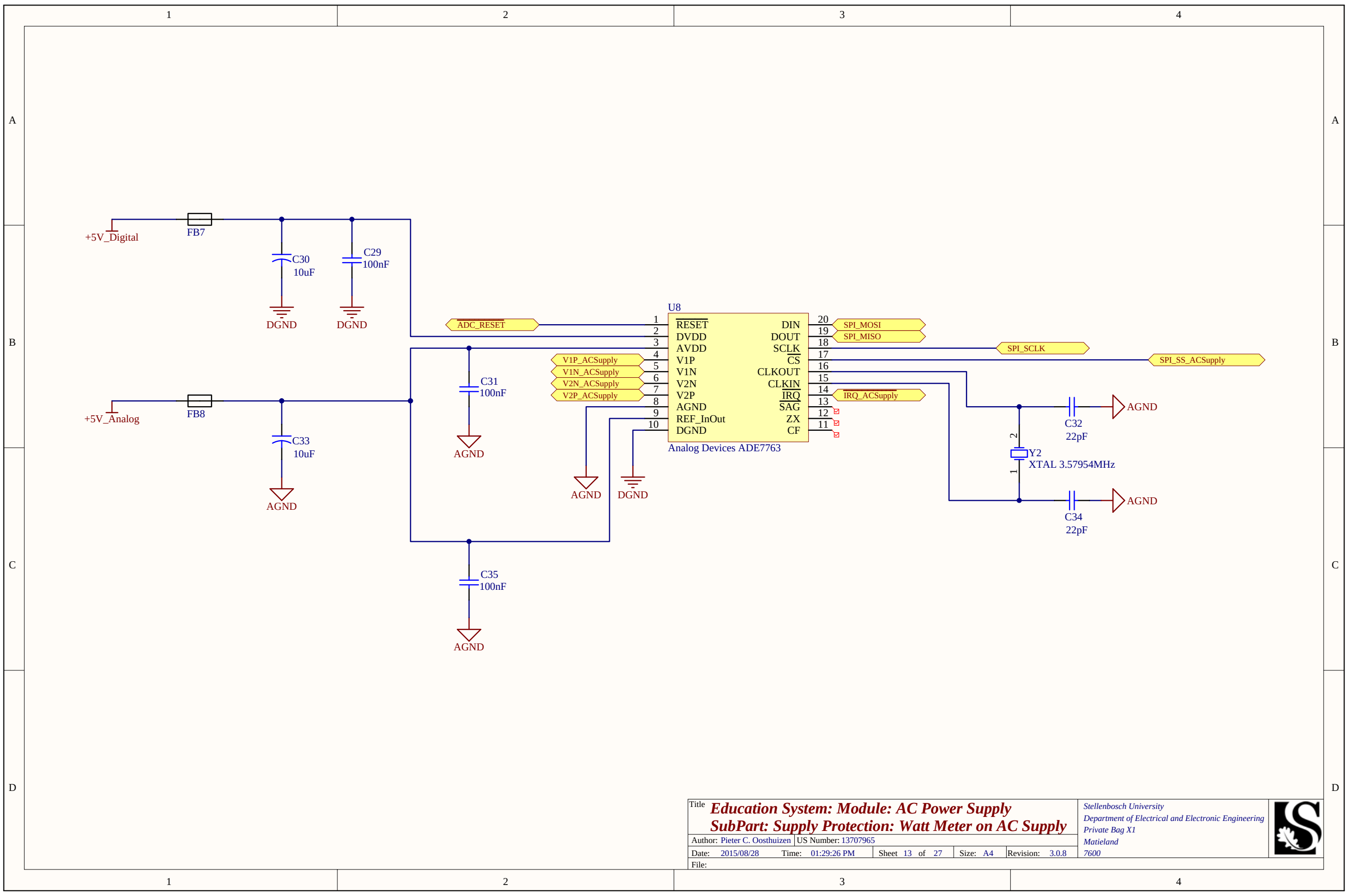
+5V_Digital
FB7
C30
10uF
C29
100nF
DGND
DGND
U8
ADC_RESET
RESET
DVDD
AVDD
V1P
V1N
V2N
V2P
AGND
REF_InOut
DGND
DIN
DOUT
SCLK
CS
CLKOUT
CLKIN
IRQ
SAG
ZX
CF
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_ACSupply
IRQ_ACSupply
V1P_ACSupply
V1N_ACSupply
V2N_ACSupply
V2P_ACSupply
Analog Devices ADE7763
+5V_Analog
FB8
C31
100nF
C33
10uF
AGND
AGND
AGND
DGND
C32
22pF
Y2
XTAL 3.57954MHz
C34
22pF
AGND
AGND
C35
100nF
AGND
Education System: Module: AC Power Supply
SubPart: Supply Protection: Watt Meter on AC Supply
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
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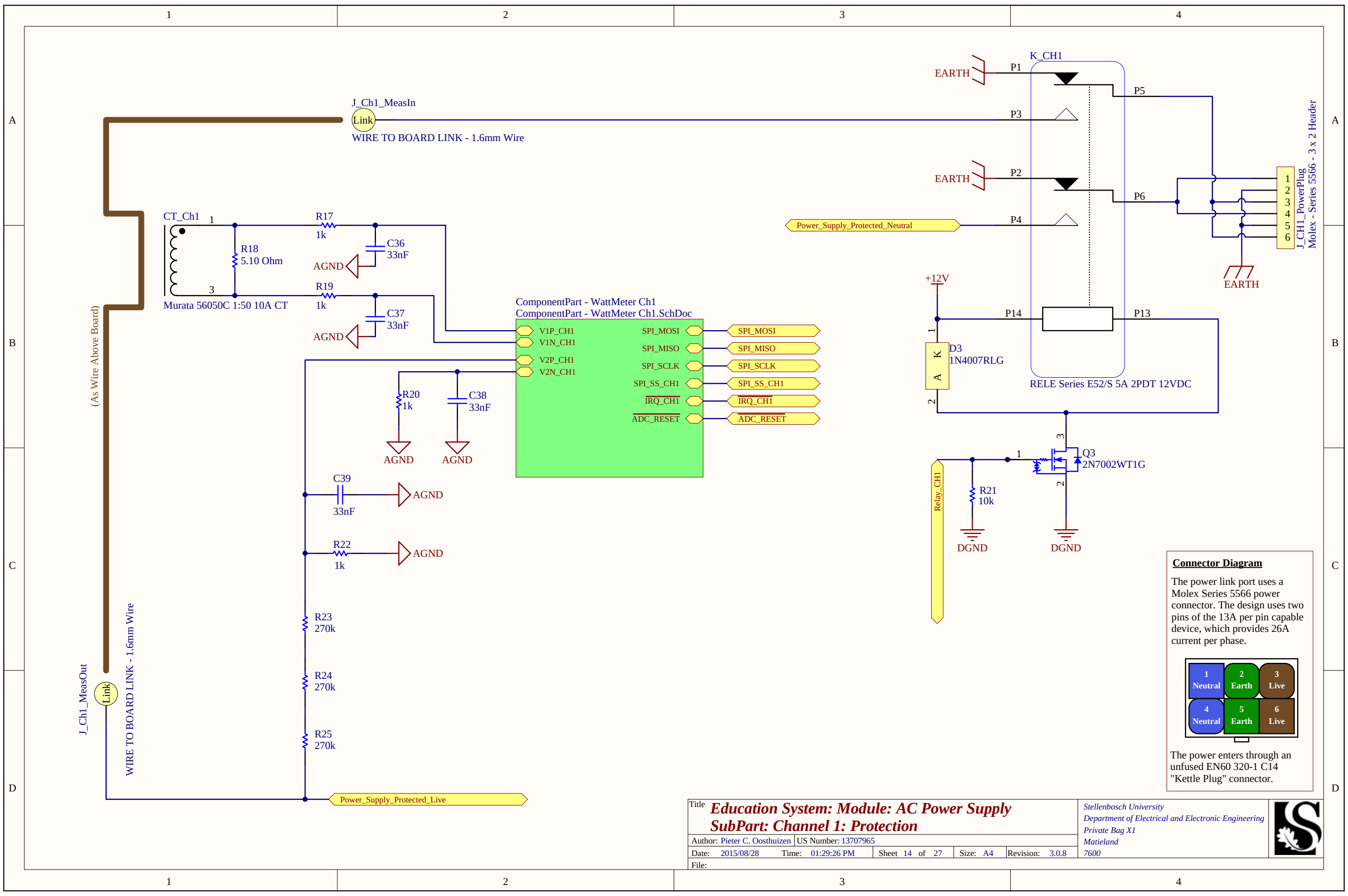
J_Ch1_MeasIn
Link
WIRE TO BOARD LINK - 1.6mm Wire
K_CH1
EARTH
P1
P3
P5
P2
P6
P4
Power_Supply_Protected_Neutral
J_CH1_PowerPlug
Molex - Series 5566 - 3 x 2 Header
CT_Ch1
Murata 56050C 1:50 10A CT
R17 1k
R18 5.10 Ohm
R19 1k
C36 33nF
C37 33nF
AGND
+12V
P14
P13
D3 1N4007RLG
RELE Series E52/S 5A 2PDT 12VDC
ComponentPart - WattMeter Ch1
ComponentPart - WattMeter Ch1.SchDoc
V1P_CH1
V1N_CH1
V2P_CH1
V2N_CH1
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH1
IRQ_CH1
ADC_RESET
R20 1k
C38 33nF
C39 33nF
R22 1k
R23 270k
R24 270k
R25 270k
Q3 2N7002WT1G
R21 10k
DGND
Relay_CH1
(As Wire Above Board)
J_Ch1_MeasOut
WIRE TO BOARD LINK - 1.6mm Wire
Power_Supply_Protected_Live
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
1 Neutral
2 Earth
3 Live
4 Neutral
5 Earth
6 Live
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
Education System: Module: AC Power Supply
SubPart: Channel 1: Protection
Author: Pieter C. Oosthuizen | US Number: 13707965
Date: 2015/08/28 Time: 01:29:26 PM Sheet 14 of 27 Size: A4 Revision: 3.0.8
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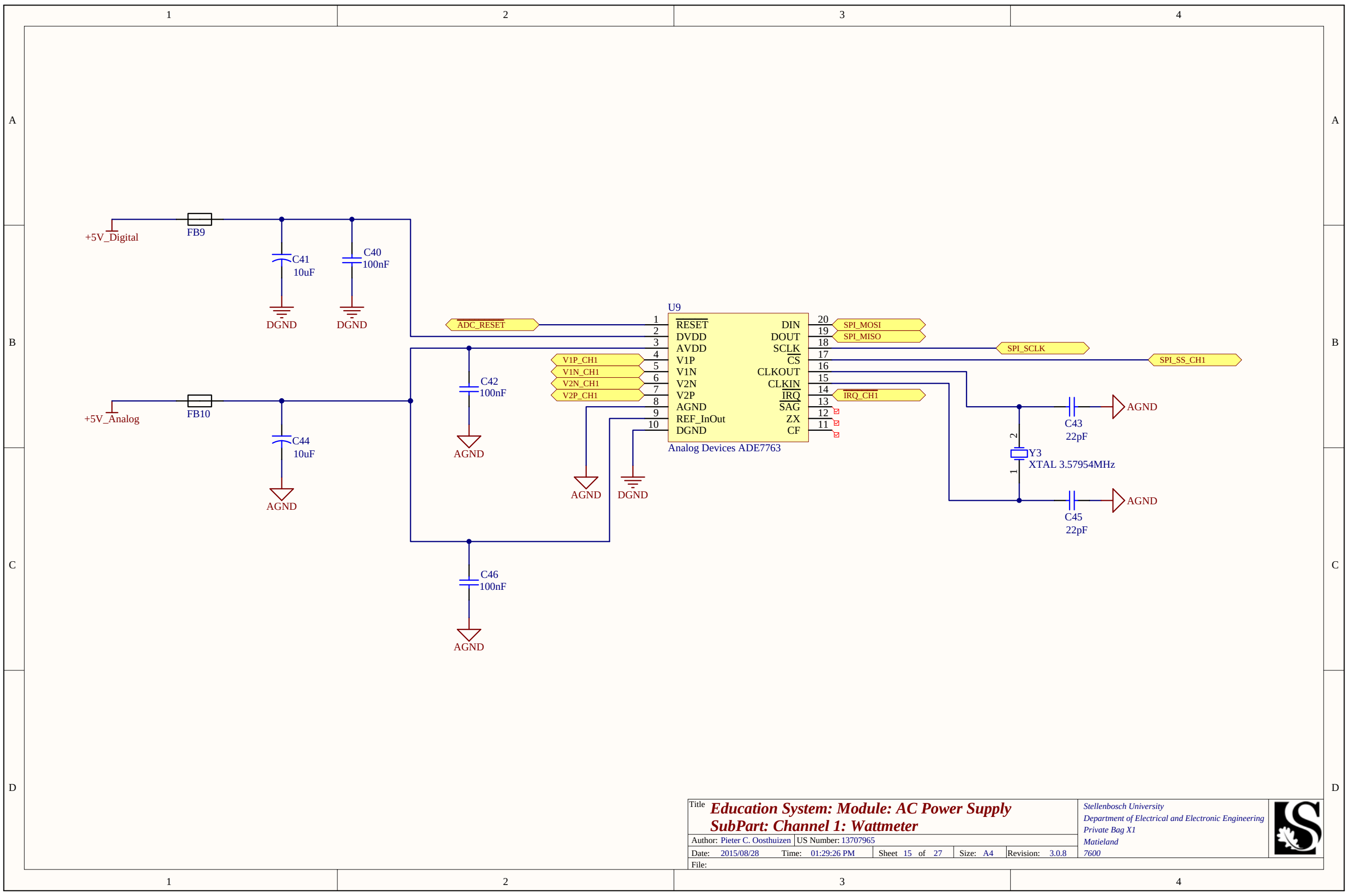
+5V_Digital
FB9
C41 10uF
C40 100nF
DGND
+5V_Analog
FB10
C44 10uF
AGND
C42 100nF
C46 100nF
ADC_RESET
U9
RESET
DVDD
AVDD
V1P
V1N
V2N
V2P
AGND
REF_InOut
DGND
DIN
DOUT
SCLK
CS
CLKOUT
CLKIN
IRQ
SAG
ZX
CF
Analog Devices ADE7763
V1P_CH1
V1N_CH1
V2N_CH1
V2P_CH1
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH1
IRQ_CH1
C43 22pF
Y3 XTAL 3.57954MHz
C45 22pF
Education System: Module: AC Power Supply
SubPart: Channel 1: Wattmeter
Author: Pieter C. Oosthuizen | US Number: 13707965
Date: 2015/08/28 Time: 01:29:26 PM Sheet 15 of 27 Size: A4 Revision: 3.0.8
File:
Stellenbosch University
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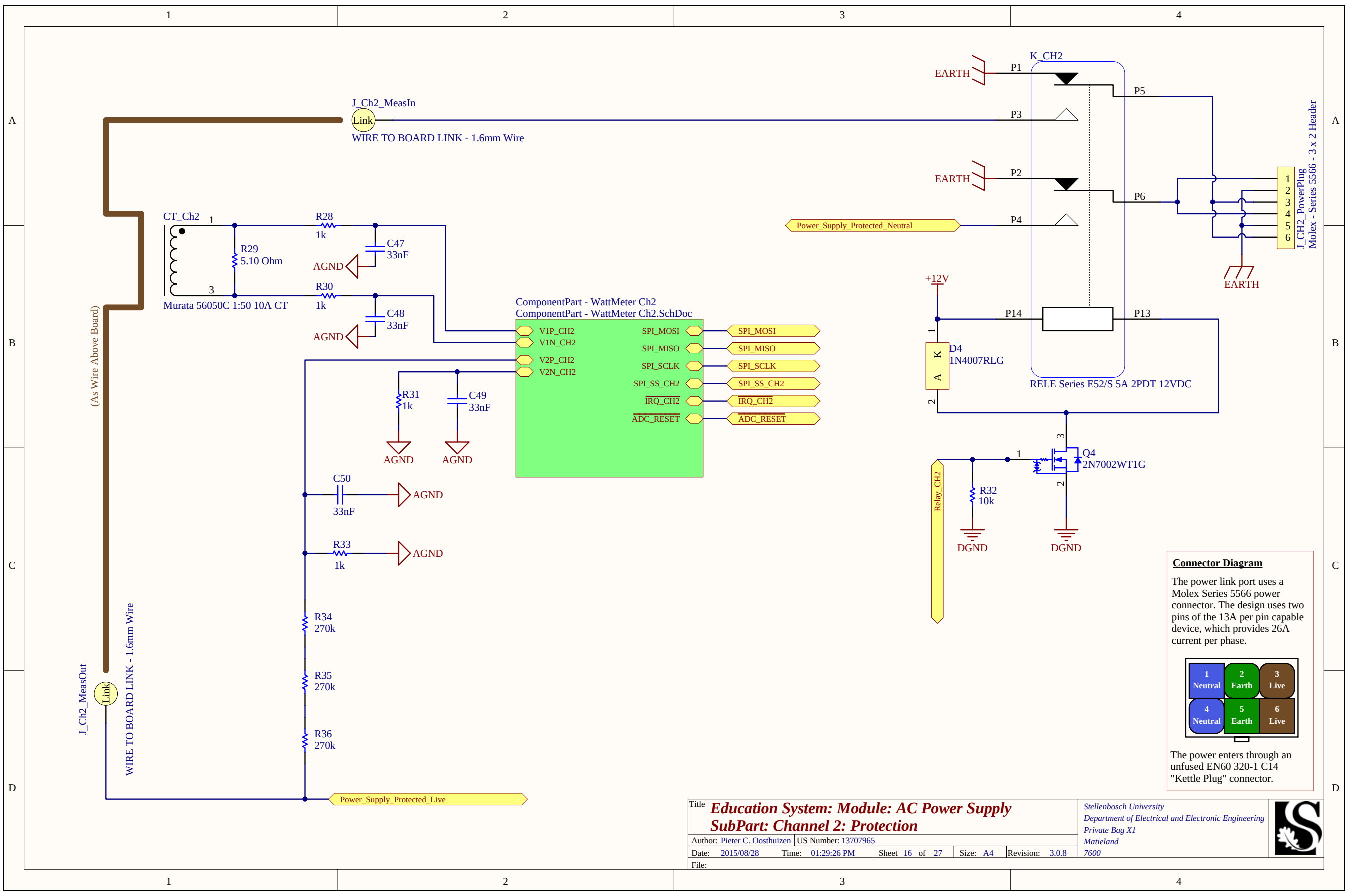

J_Ch2_MeasIn
WIRE TO BOARD LINK - 1.6mm Wire
Link
EARTH
K_CH2
P1
P2
P3
P4
P5
P6
P13
P14
Power_Supply_Protected_Neutral
J_CH2_PowerPlug
Molex - Series 5566 - 3 x 2 Header
CT_Ch2
Murata 56050C 1:50 10A CT
R28 1k
R29 5.10 Ohm
R30 1k
C47 33nF
C48 33nF
AGND
ComponentPart - WattMeter Ch2
ComponentPart - WattMeter Ch2.SchDoc
V1P_CH2
V1N_CH2
V2P_CH2
V2N_CH2
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH2
IRQ_CH2
ADC_RESET
R31 1k
C49 33nF
C50 33nF
R33 1k
R34 270k
R35 270k
R36 270k
Power_Supply_Protected_Live
(As Wire Above Board)
J_Ch2_MeasOut
WIRE TO BOARD LINK - 1.6mm Wire
+12V
D4 1N4007RLG
RELE Series E52/S 5A 2PDT 12VDC
Q4 2N7002WT1G
R32 10k
DGND
Relay_CH2
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
1 Neutral
2 Earth
3 Live
4 Neutral
5 Earth
6 Live
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
Title Education System: Module: AC Power Supply
SubPart: Channel 2: Protection
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:26 PM
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Size: A4
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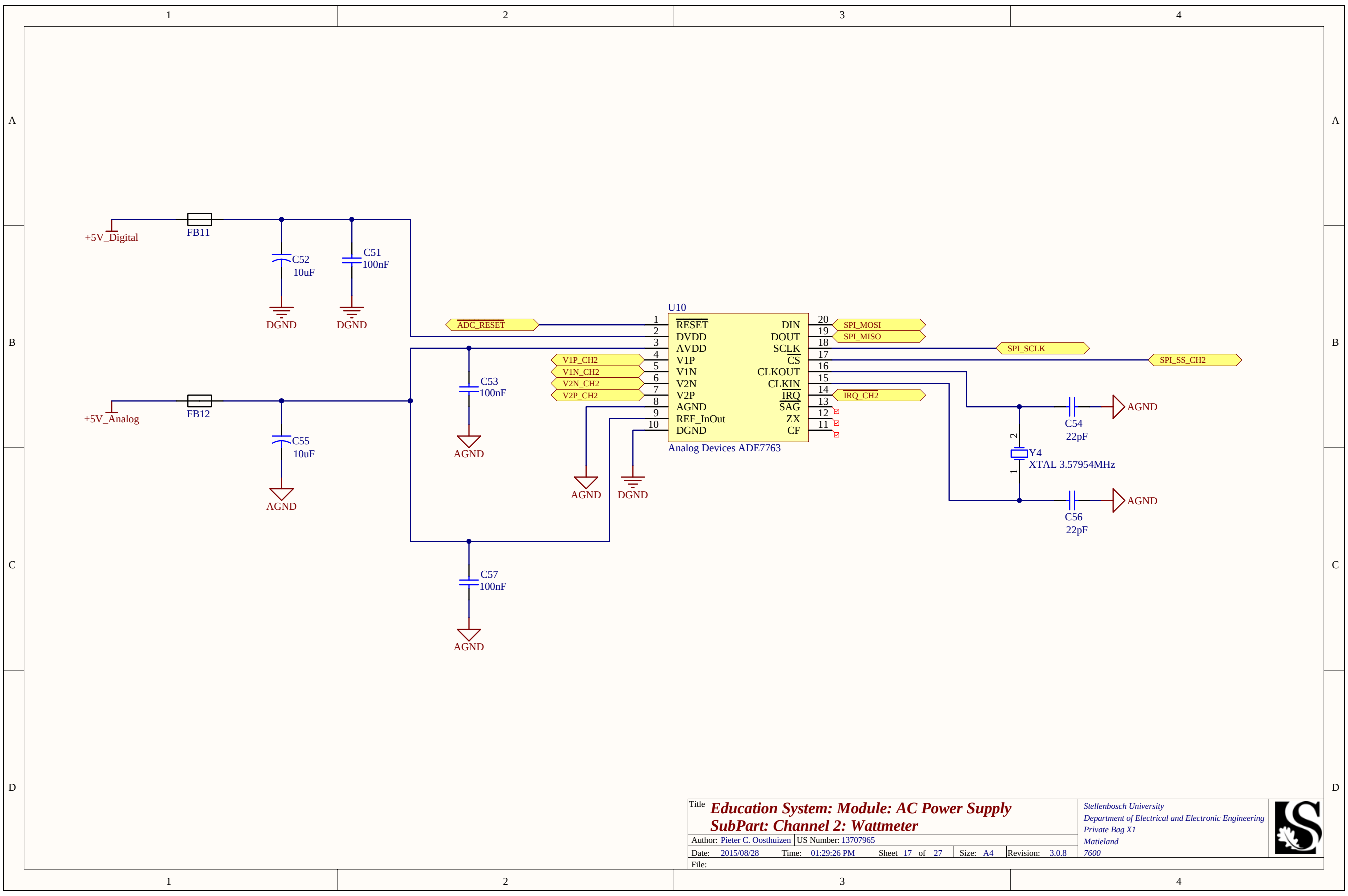

+5V_Digital
FB11
C52 10uF
C51 100nF
DGND
+5V_Analog
FB12
C55 10uF
AGND
ADC_RESET
U10
RESET
DVDD
AVDD
V1P
V1N
V2N
V2P
AGND
REF_InOut
DGND
DIN
DOUT
SCLK
CS
CLKOUT
CLKIN
IRQ
SAG
ZX
CF
Analog Devices ADE7763
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH2
IRQ_CH2
V1P_CH2
V1N_CH2
V2N_CH2
V2P_CH2
C53 100nF
C57 100nF
C54 22pF
C56 22pF
Y4 XTAL 3.57954MHz
Title Education System: Module: AC Power Supply
SubPart: Channel 2: Wattmeter
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
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Size: A4
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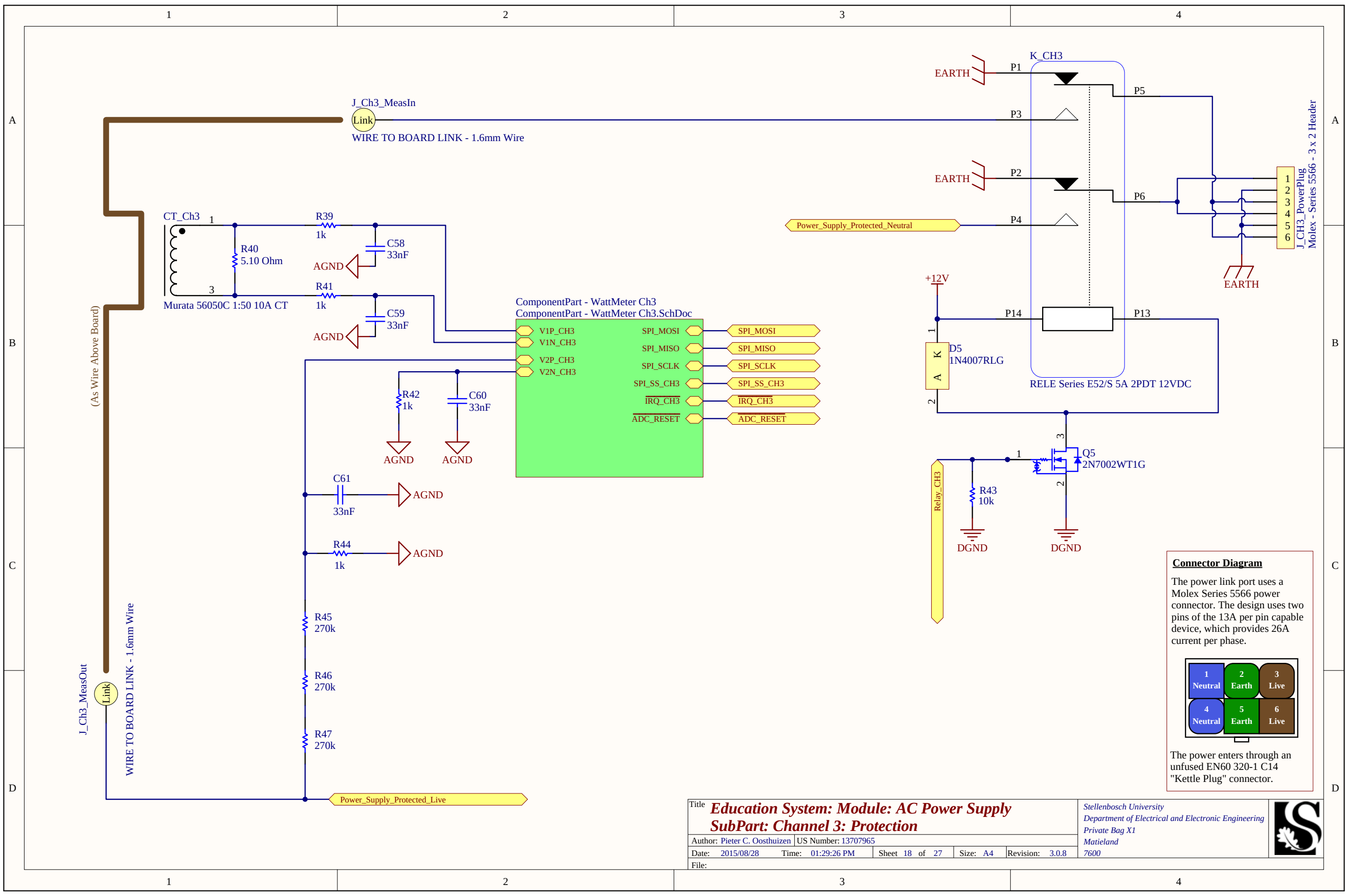
Education System: Module: AC Power Supply
SubPart: Channel 3: Protection
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:26 PM
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Size: A4
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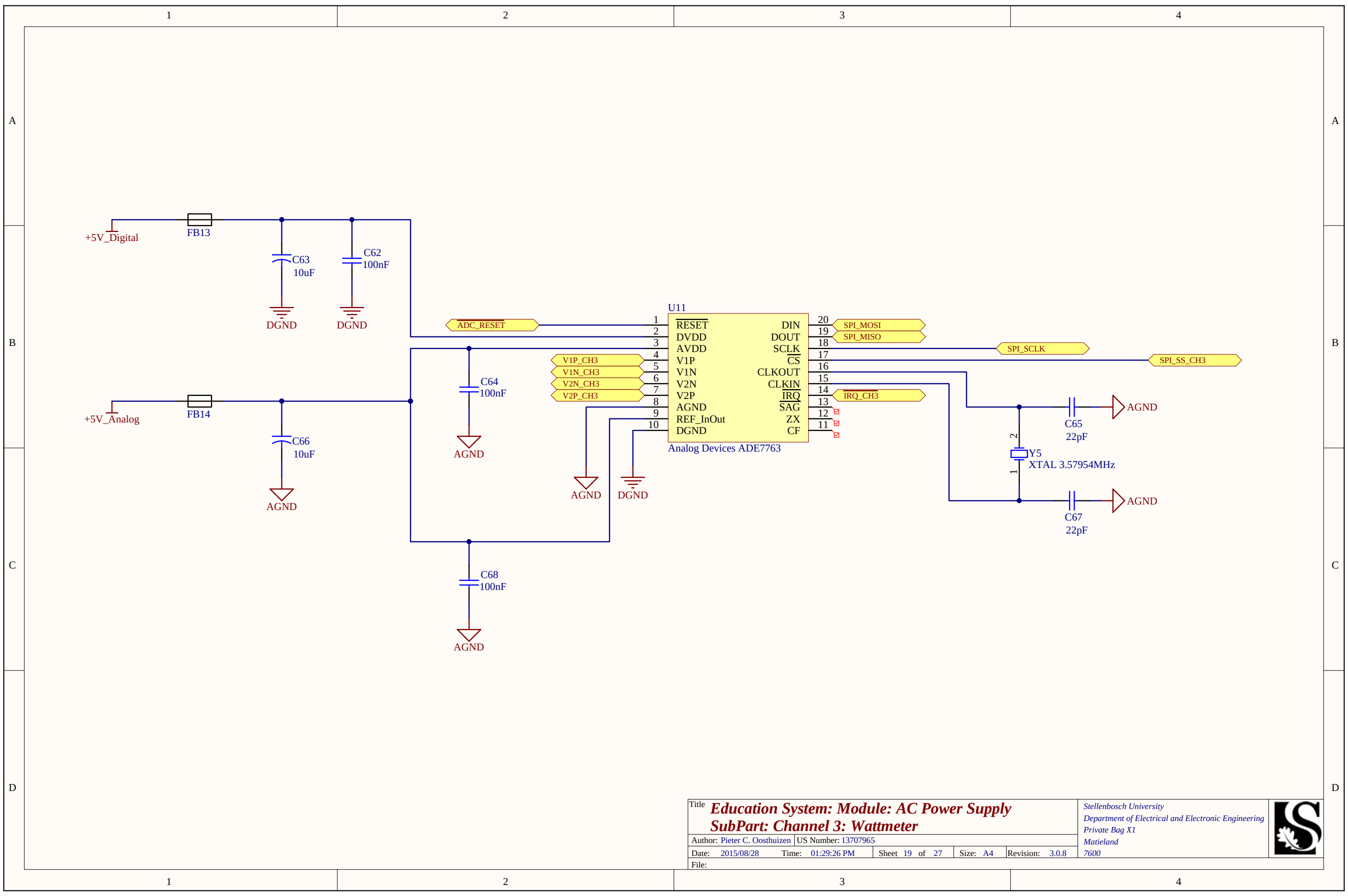
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
K_CH3
RELE Series E52/S 5A 2PDT 12VDC
J_Ch3_MeasIn
WIRE TO BOARD LINK - 1.6mm Wire
CT_Ch3
Murata 56050C 1:50 10A CT
ComponentPart - WattMeter Ch3
ComponentPart - WattMeter Ch3.SchDoc
D5
1N4007RLG
Q5
2N7002WT1G
J_CH3_PowerPlug
Molex - Series 5566 - 3 x 2 Header
Power_Supply_Protected_Neutral
Power_Supply_Protected_Live


Education System: Module: AC Power Supply
SubPart: Channel 3: Wattmeter
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:26 PM
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Size: A4
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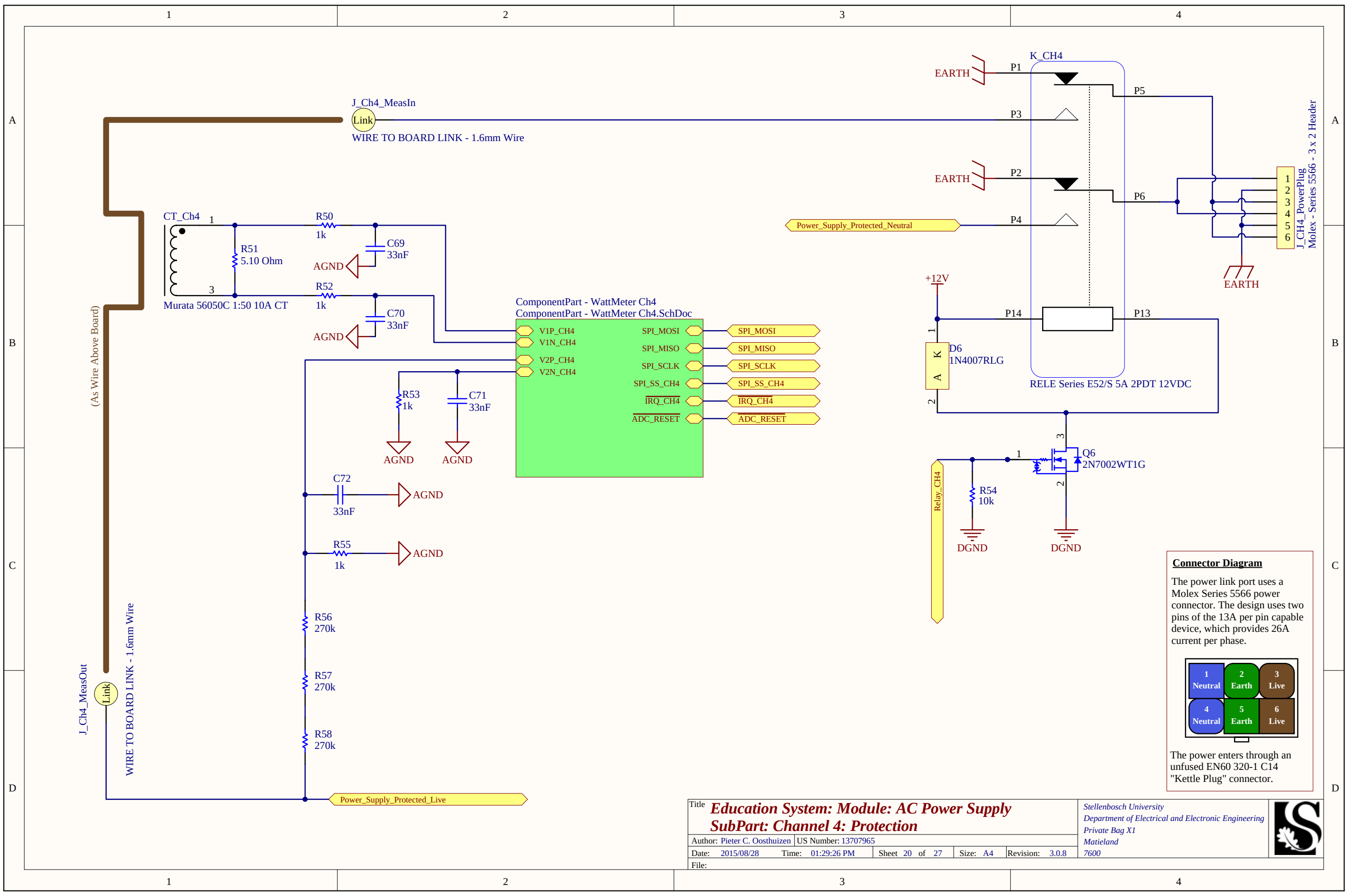
7600
U11
Analog Devices ADE7763
Y5
XTAL 3.57954MHz
+5V_Digital
+5V_Analog



Education System: Module: AC Power Supply
SubPart: Channel 4: Protection
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28 Time: 01:29:26 PM Sheet 20 of 27 Size: A4 Revision: 3.0.8
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Department of Electrical and Electronic Engineering
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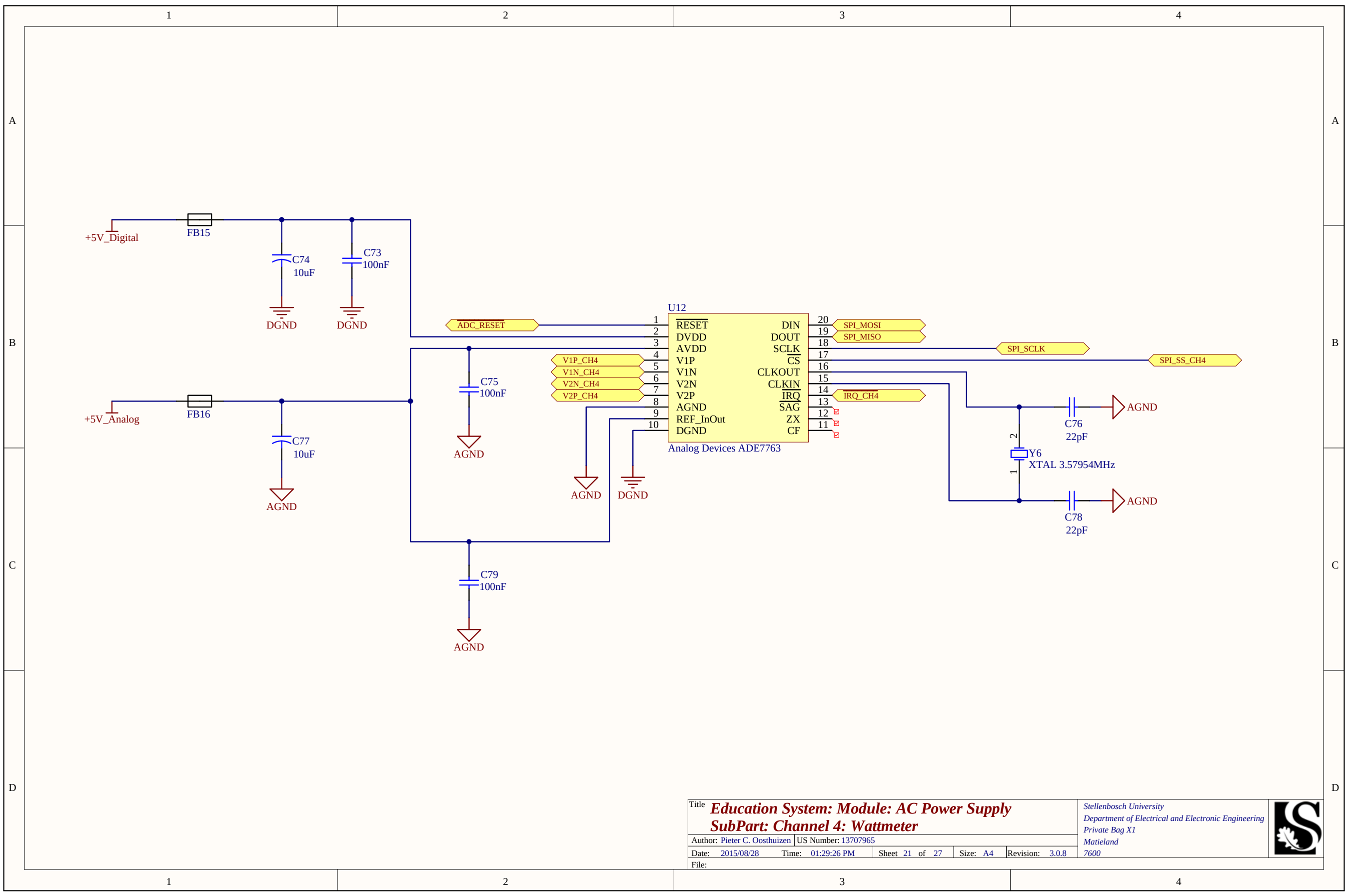
7600
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
J_Ch4_MeasIn
WIRE TO BOARD LINK - 1.6mm Wire
CT_Ch4
Murata 56050C 1:50 10A CT
ComponentPart - WattMeter Ch4
ComponentPart - WattMeter Ch4.SchDoc
K_CH4
RELE Series E52/S 5A 2PDT 12VDC
D6
1N4007RLG
Q6
2N7002WT1G
J_CH4_PowerPlug
Molex - Series 5566 - 3 x 2 Header
Power_Supply_Protected_Neutral
Power_Supply_Protected_Live



Education System: Module: AC Power Supply
SubPart: Channel 4: Wattmeter
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28 Time: 01:29:26 PM Sheet 21 of 27 Size: A4 Revision: 3.0.8
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Department of Electrical and Electronic Engineering
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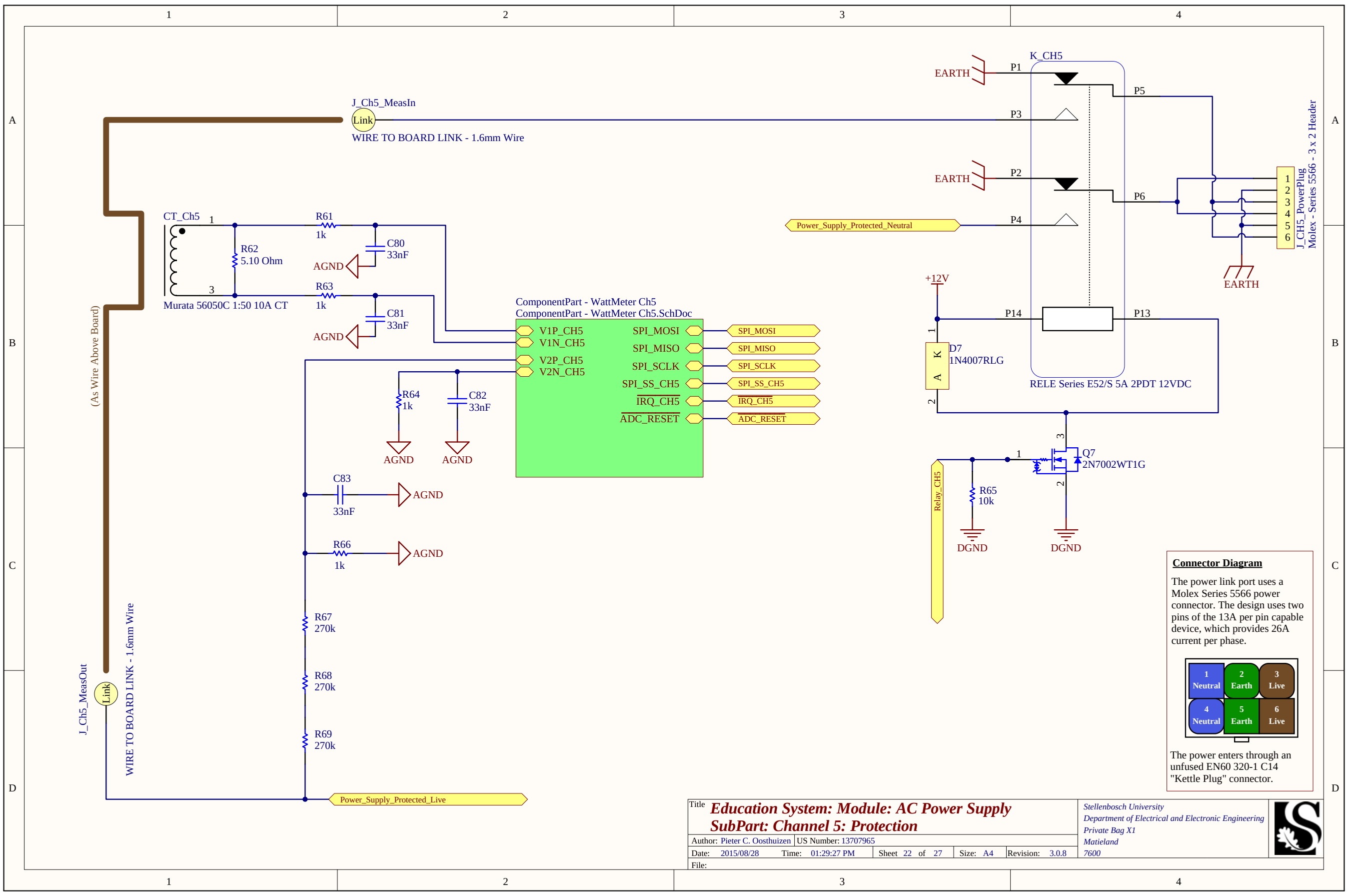
7600
U12
Analog Devices ADE7763
XTAL 3.57954MHz


J_Ch5_MeasIn
Link
WIRE TO BOARD LINK - 1.6mm Wire
K_CH5
EARTH
P1
P3
P5
P2
P4
P6
Power_Supply_Protected_Neutral
J_CH5_PowerPlug
Molex - Series 5566 - 3 x 2 Header
EARTH
CT_Ch5
R61
1k
C80
33nF
R62
5.10 Ohm
AGND
R63
1k
C81
33nF
Murata 56050C 1:50 10A CT
ComponentPart - WattMeter Ch5
ComponentPart - WattMeter Ch5.SchDoc
V1P_CH5
V1N_CH5
V2P_CH5
V2N_CH5
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH5
IRQ_CH5
ADC_RESET
R64
1k
C82
33nF
C83
33nF
R66
1k
R67
270k
R68
270k
R69
270k
Power_Supply_Protected_Live
(As Wire Above Board)
J_Ch5_MeasOut
WIRE TO BOARD LINK - 1.6mm Wire
+12V
P14
P13
D7
1N4007RLG
RELE Series E52/S 5A 2PDT 12VDC
Q7
2N7002WT1G
R65
10k
DGND
Relay_CH5
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
1 Neutral
2 Earth
3 Live
4 Neutral
5 Earth
6 Live
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
Education System: Module: AC Power Supply
SubPart: Channel 5: Protection
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:27 PM
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Size: A4
Revision: 3.0.8
File:
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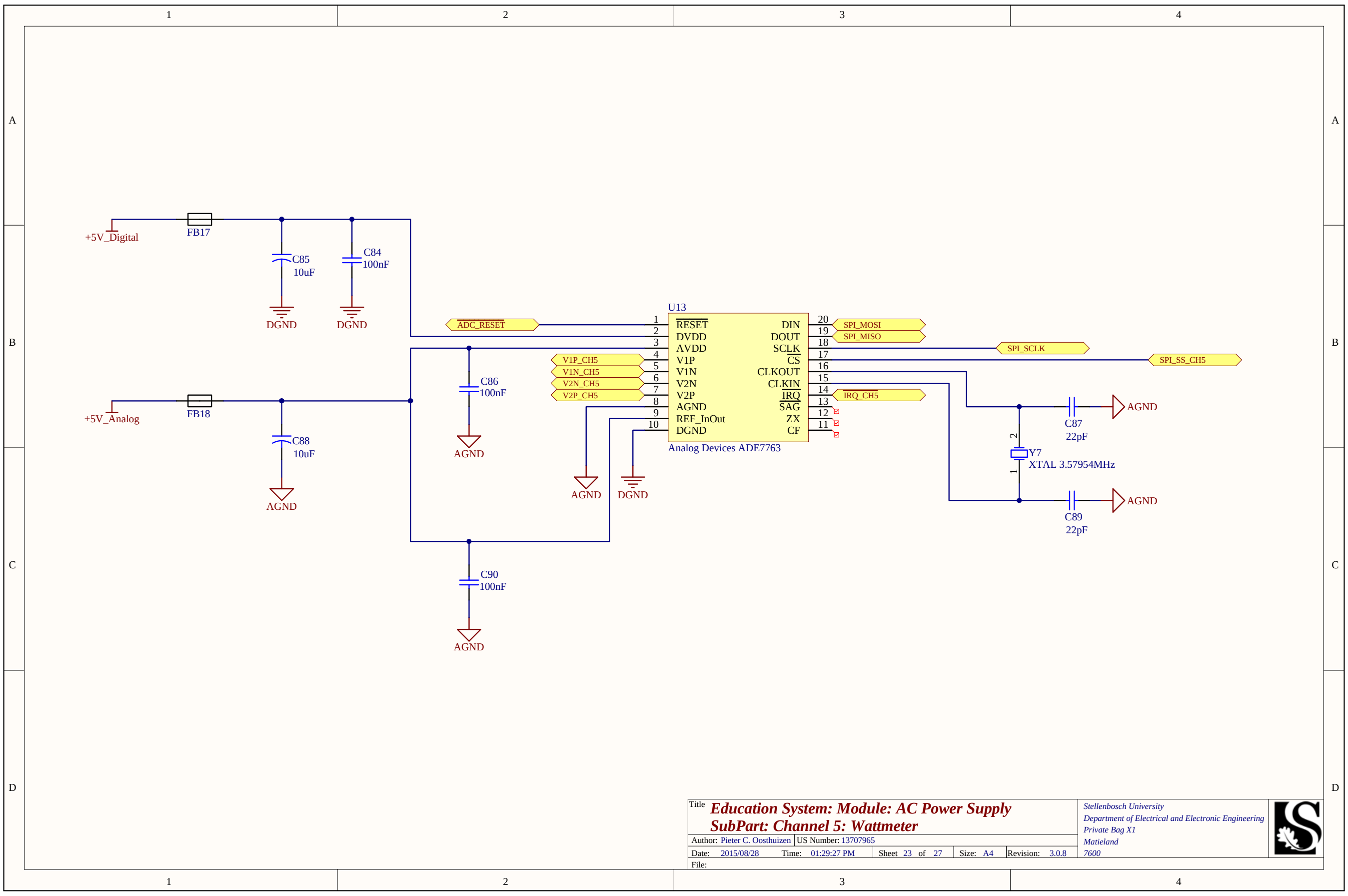
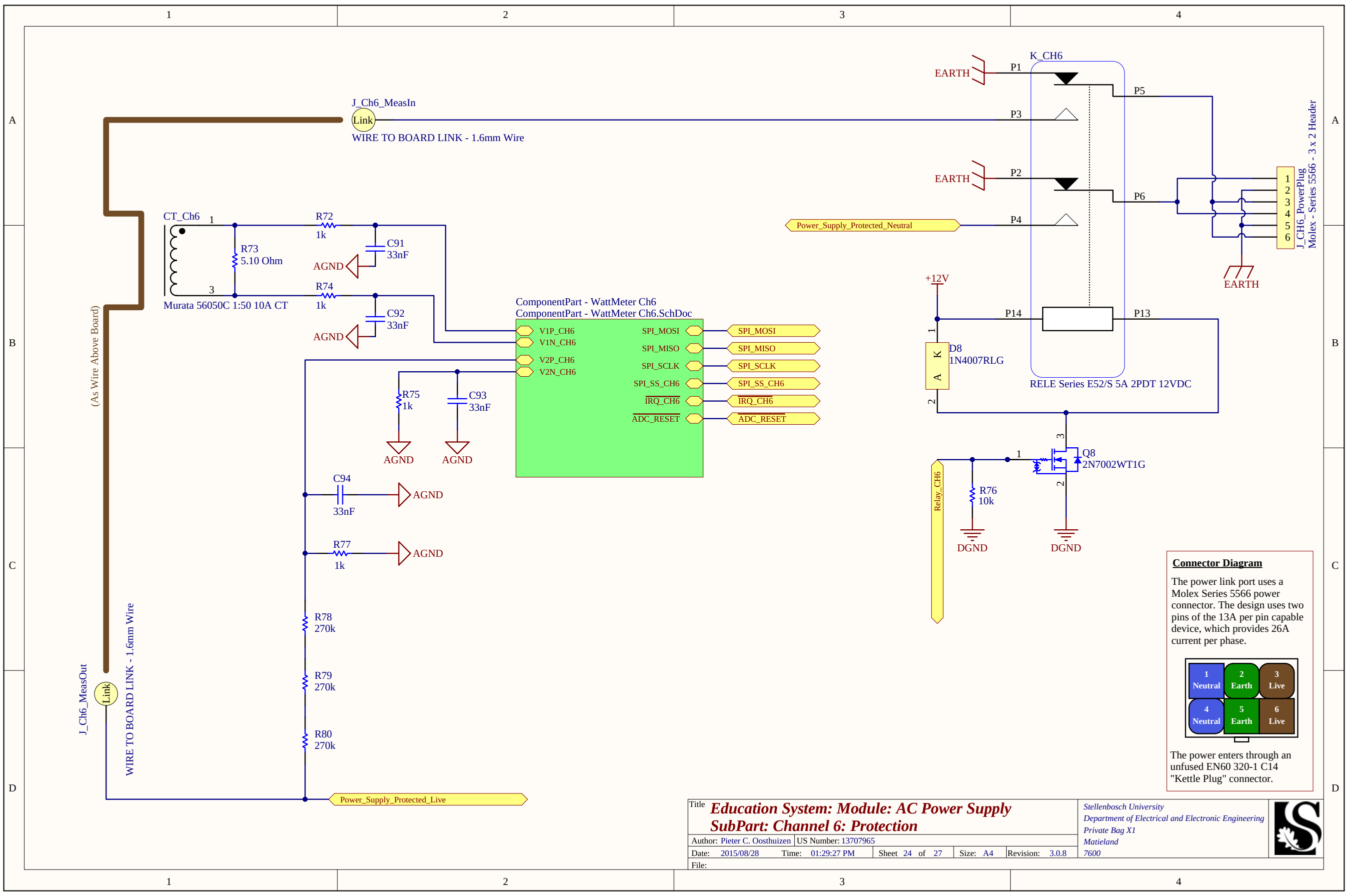
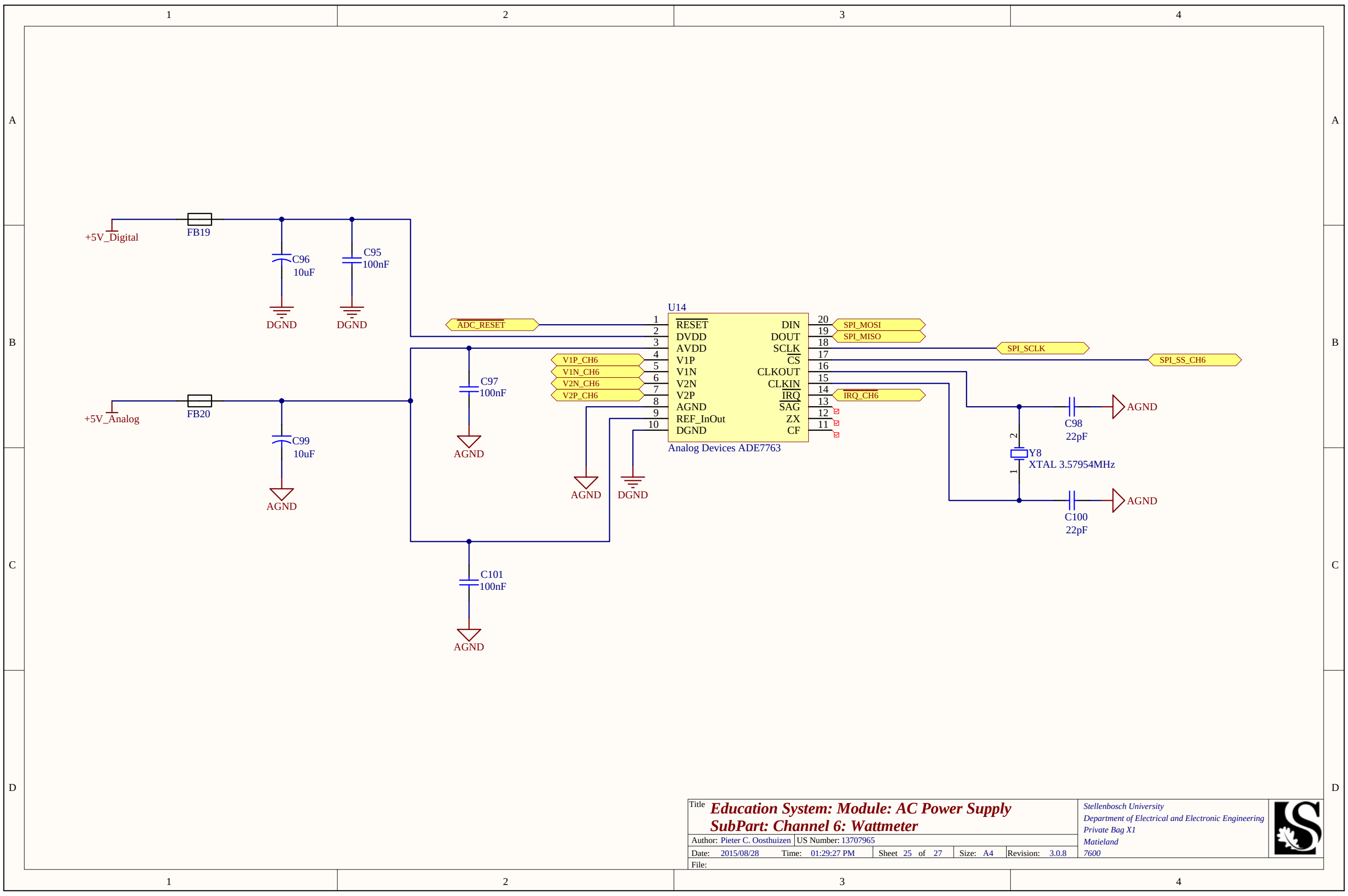

+5V_Digital
FB17
C85
10uF
C84
100nF
DGND
+5V_Analog
FB18
C88
10uF
AGND
U13
ADC_RESET
RESET
DVDD
AVDD
V1P
V1N
V2N
V2P
AGND
REF_InOut
DGND
DIN
DOUT
SCLK
CS
CLKOUT
CLKIN
IRQ
SAG
ZX
CF
Analog Devices ADE7763
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH5
IRQ_CH5
V1P_CH5
V1N_CH5
V2N_CH5
V2P_CH5
C86
100nF
C87
22pF
Y7
XTAL 3.57954MHz
C89
22pF
C90
100nF
Education System: Module: AC Power Supply
SubPart: Channel 5: Wattmeter
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:27 PM
Sheet 23 of 27
Size: A4
Revision: 3.0.8
File:
Stellenbosch University
Department of Electrical and Electronic Engineering
Private Bag X1
Matieland
7600


Education System: Module: AC Power Supply
SubPart: Channel 6: Protection
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
J_Ch6_MeasIn
WIRE TO BOARD LINK - 1.6mm Wire
CT_Ch6
Murata 56050C 1:50 10A CT
K_CH6
RELE Series E52/S 5A 2PDT 12VDC
D8
1N4007RLG
Q8
2N7002WT1G
J_CH6_PowerPlug
Molex - Series 5566 - 3 x 2 Header
ComponentPart - WattMeter Ch6
ComponentPart - WattMeter Ch6.SchDoc
Power_Supply_Protected_Neutral
Power_Supply_Protected_Live
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:27 PM
Sheet 24 of 27
Size: A4
Revision: 3.0.8
Stellenbosch University
Department of Electrical and Electronic Engineering
Private Bag X1
Matieland
7600


Education System: Module: AC Power Supply
SubPart: Channel 6: Wattmeter
U14
Analog Devices ADE7763
Y8
XTAL 3.57954MHz
+5V_Digital
+5V_Analog
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:27 PM
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Size: A4
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Stellenbosch University
Department of Electrical and Electronic Engineering
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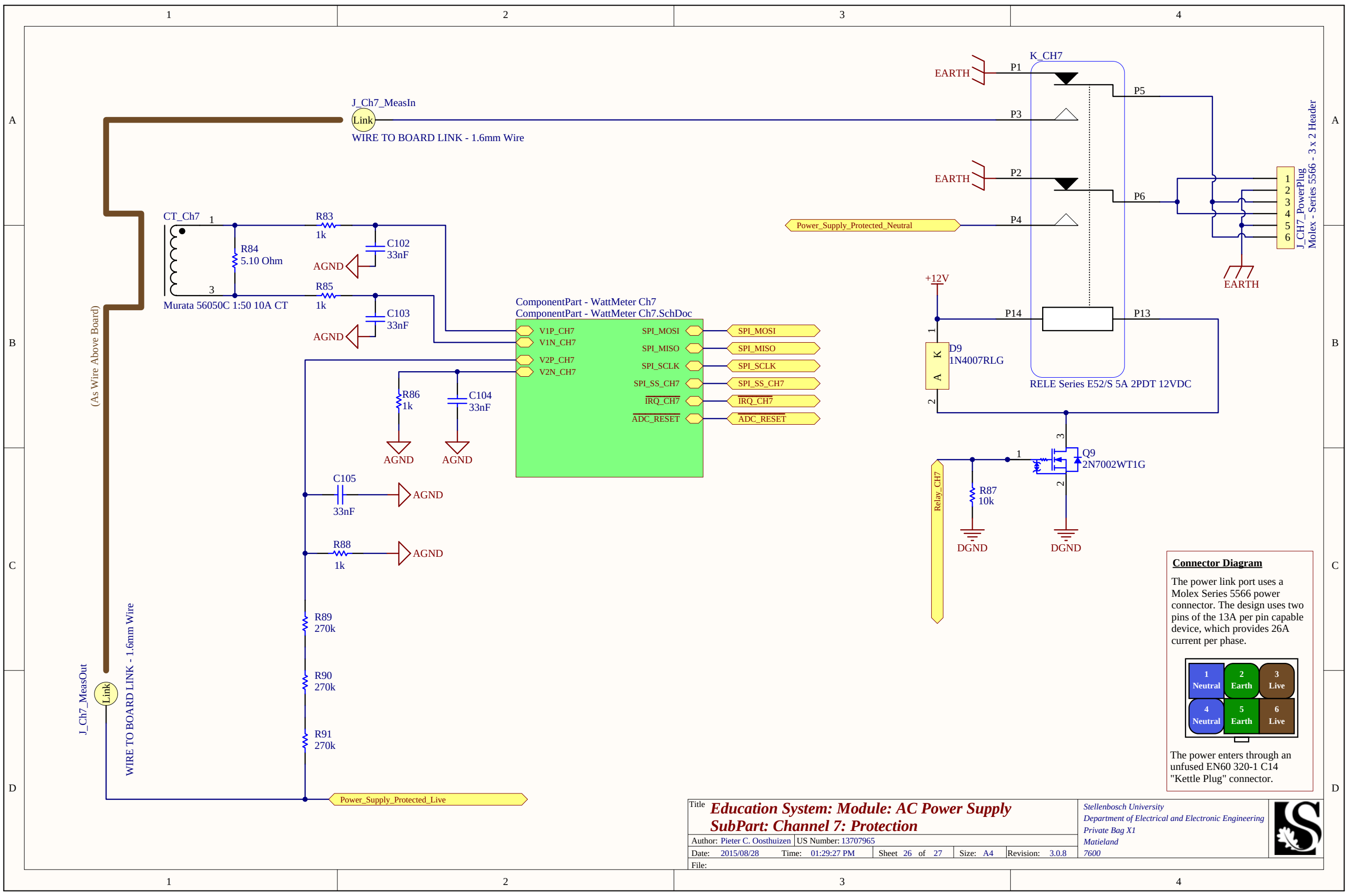
K_CH7
EARTH
P1
P5
J_Ch7_MeasIn
Link
WIRE TO BOARD LINK - 1.6mm Wire
P3
EARTH
P2
P6
Power_Supply_Protected_Neutral
P4
J_CH7_PowerPlug
Molex - Series 5566 - 3 x 2 Header
EARTH
CT_Ch7
R83
1k
C102
33nF
R84
5.10 Ohm
AGND
R85
1k
C103
33nF
Murata 56050C 1:50 10A CT
ComponentPart - WattMeter Ch7
ComponentPart - WattMeter Ch7.SchDoc
V1P_CH7
V1N_CH7
V2P_CH7
V2N_CH7
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH7
IRQ_CH7
ADC_RESET
R86
1k
C104
33nF
+12V
P14
P13
D9
1N4007RLG
RELE Series E52/S 5A 2PDT 12VDC
Q9
2N7002WT1G
Relay_CH7
R87
10k
DGND
C105
33nF
R88
1k
(As Wire Above Board)
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
1 Neutral
2 Earth
3 Live
4 Neutral
5 Earth
6 Live
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
R89
270k
R90
270k
R91
270k
J_Ch7_MeasOut
WIRE TO BOARD LINK - 1.6mm Wire
Power_Supply_Protected_Live
Education System: Module: AC Power Supply
SubPart: Channel 7: Protection
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:27 PM
Sheet 26 of 27
Size: A4
Revision: 3.0.8
Stellenbosch University
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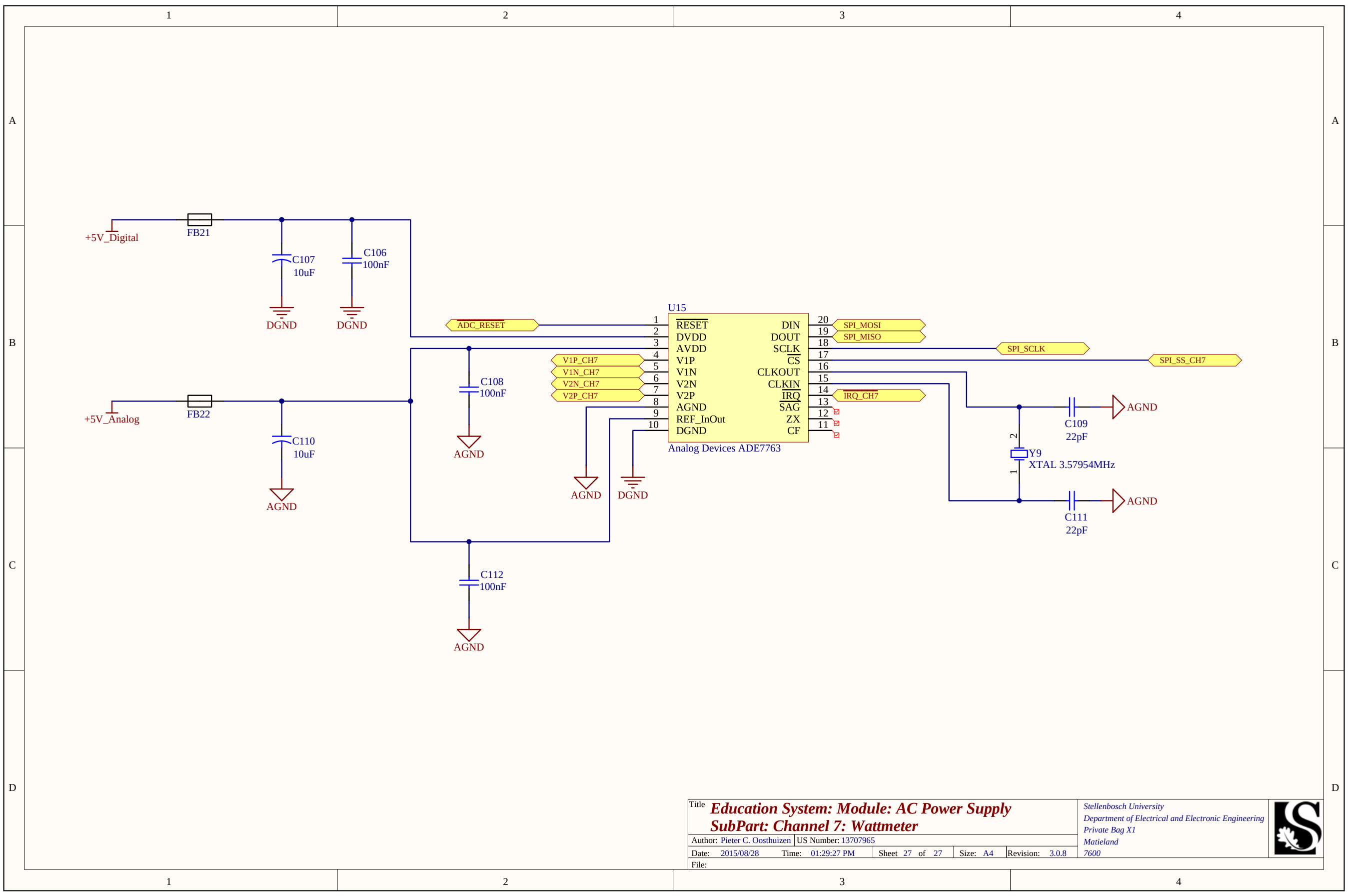
+5V_Digital
FB21
C107
10uF
C106
100nF
DGND
U15
ADC_RESET
RESET
DVDD
AVDD
V1P
V1N
V2N
V2P
AGND
REF_InOut
DGND
DIN
DOUT
SCLK
CS
CLKOUT
CLKIN
IRQ
SAG
ZX
CF
Analog Devices ADE7763
SPI_MOSI
SPI_MISO
SPI_SCLK
SPI_SS_CH7
IRQ_CH7
V1P_CH7
V1N_CH7
V2N_CH7
V2P_CH7
C108
100nF
+5V_Analog
FB22
C110
10uF
AGND
C109
22pF
Y9
XTAL 3.57954MHz
C111
22pF
C112
100nF
Education System: Module: AC Power Supply
SubPart: Channel 7: Wattmeter
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:29:27 PM
Sheet 27 of 27
Size: A4
Revision: 3.0.8
Stellenbosch University
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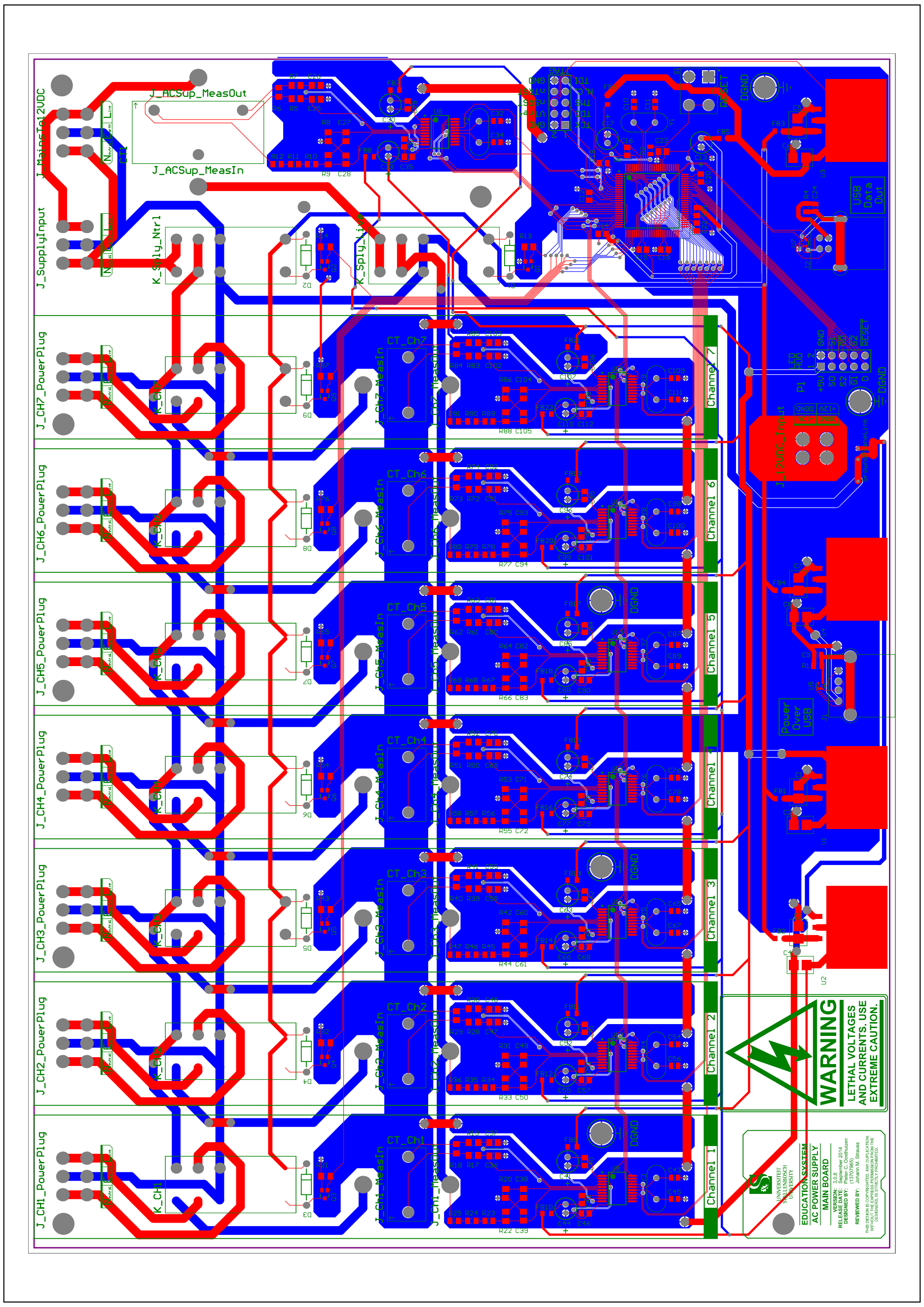
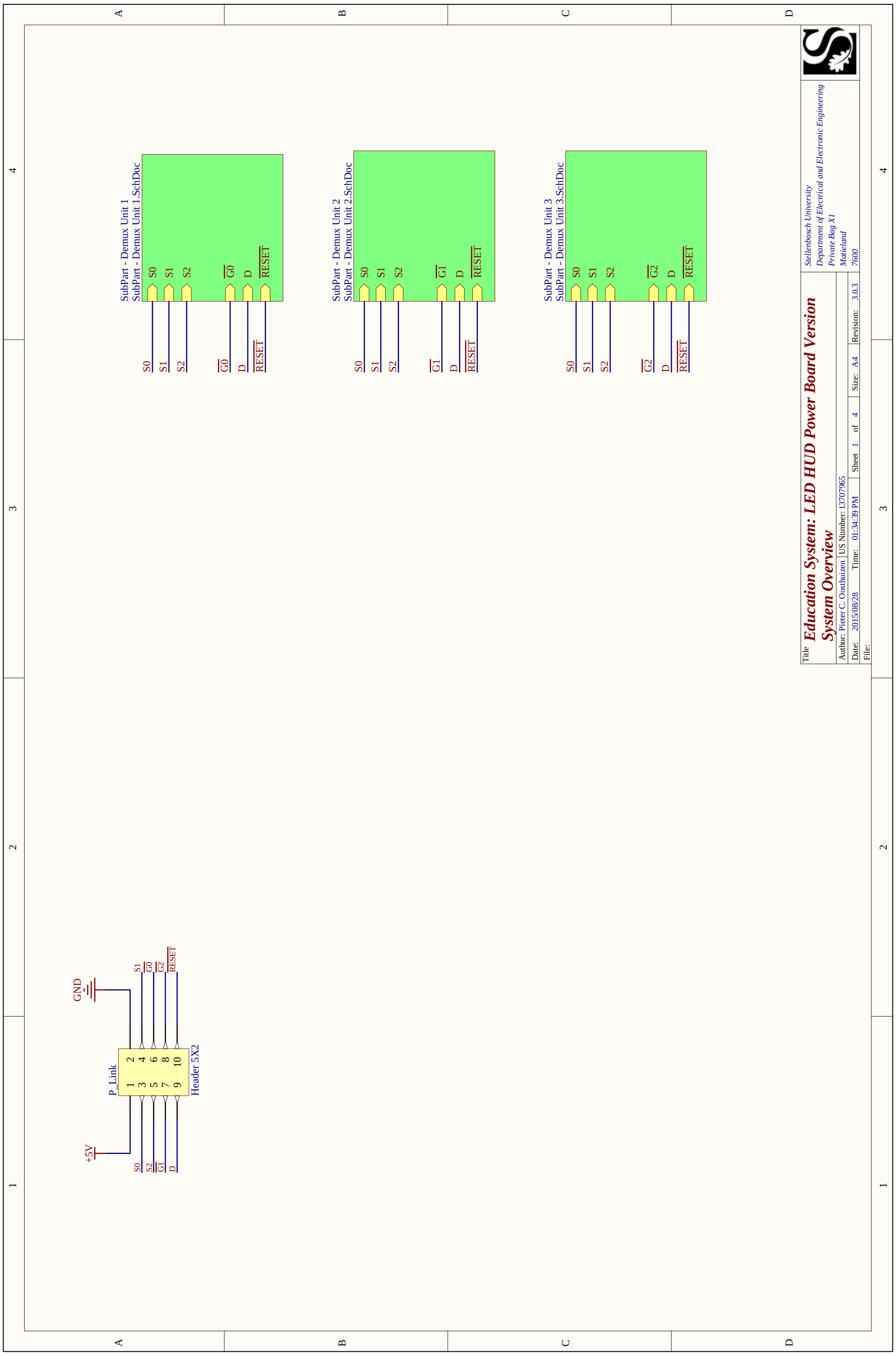
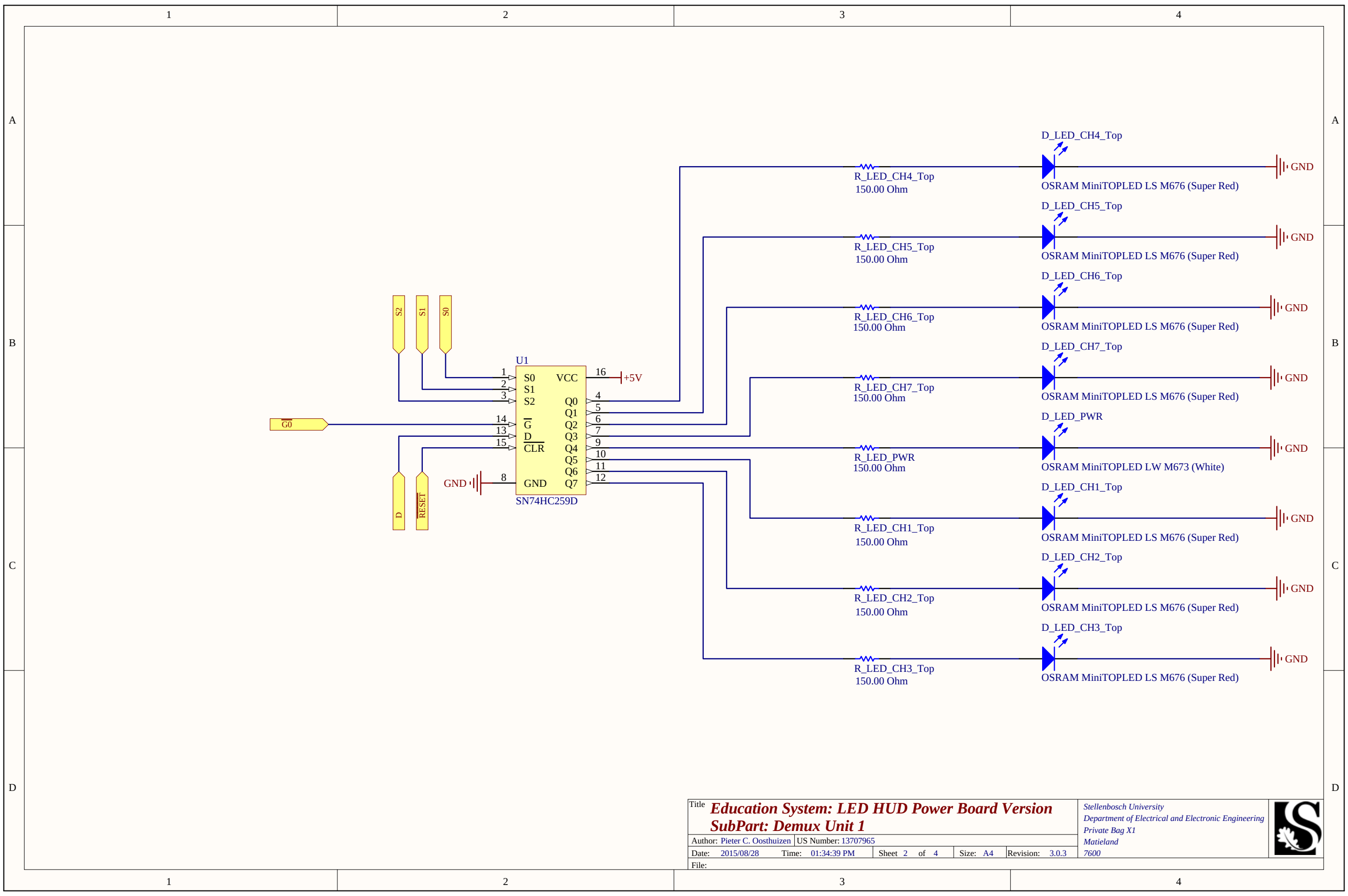
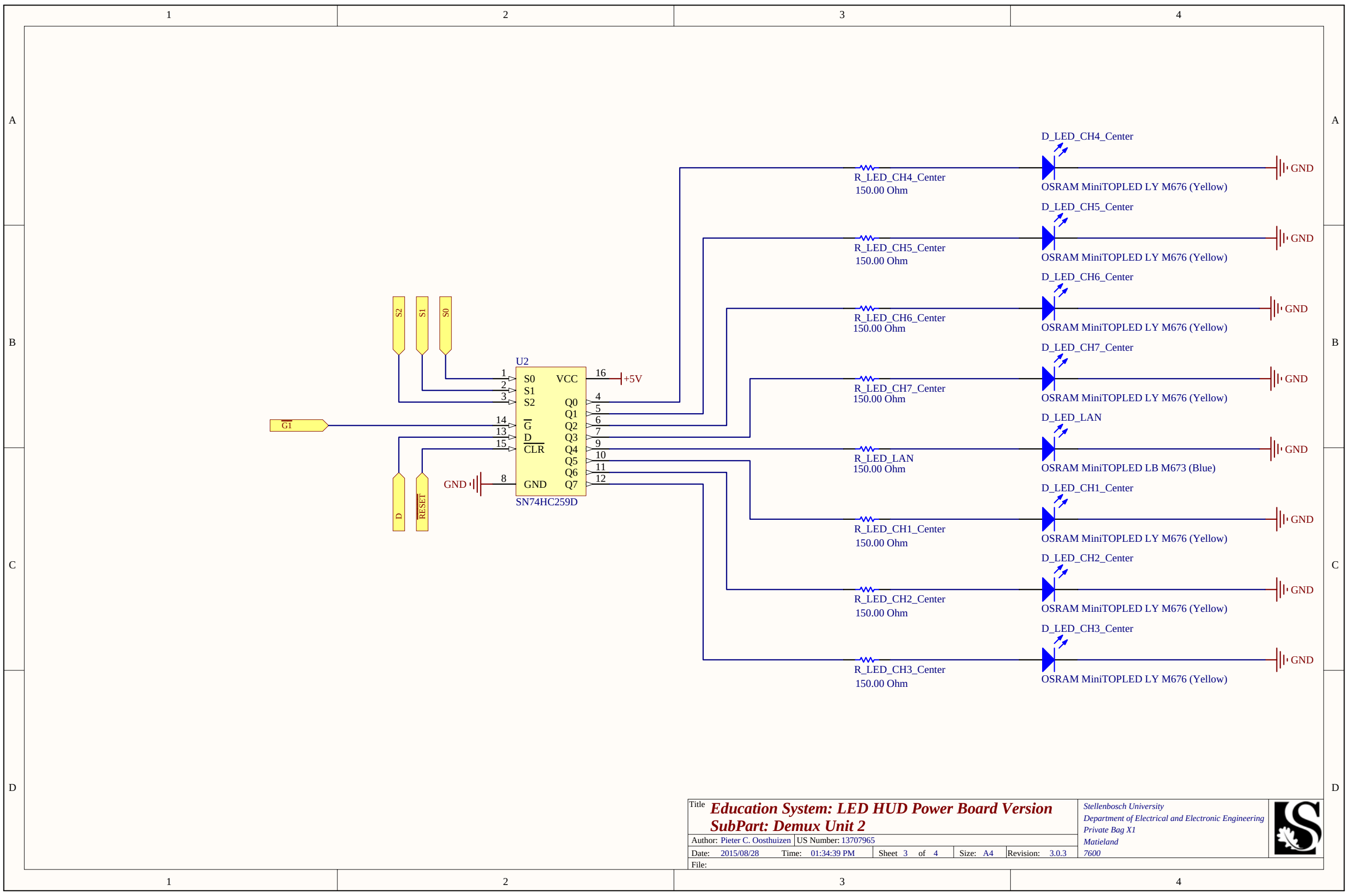
Matieland
7600

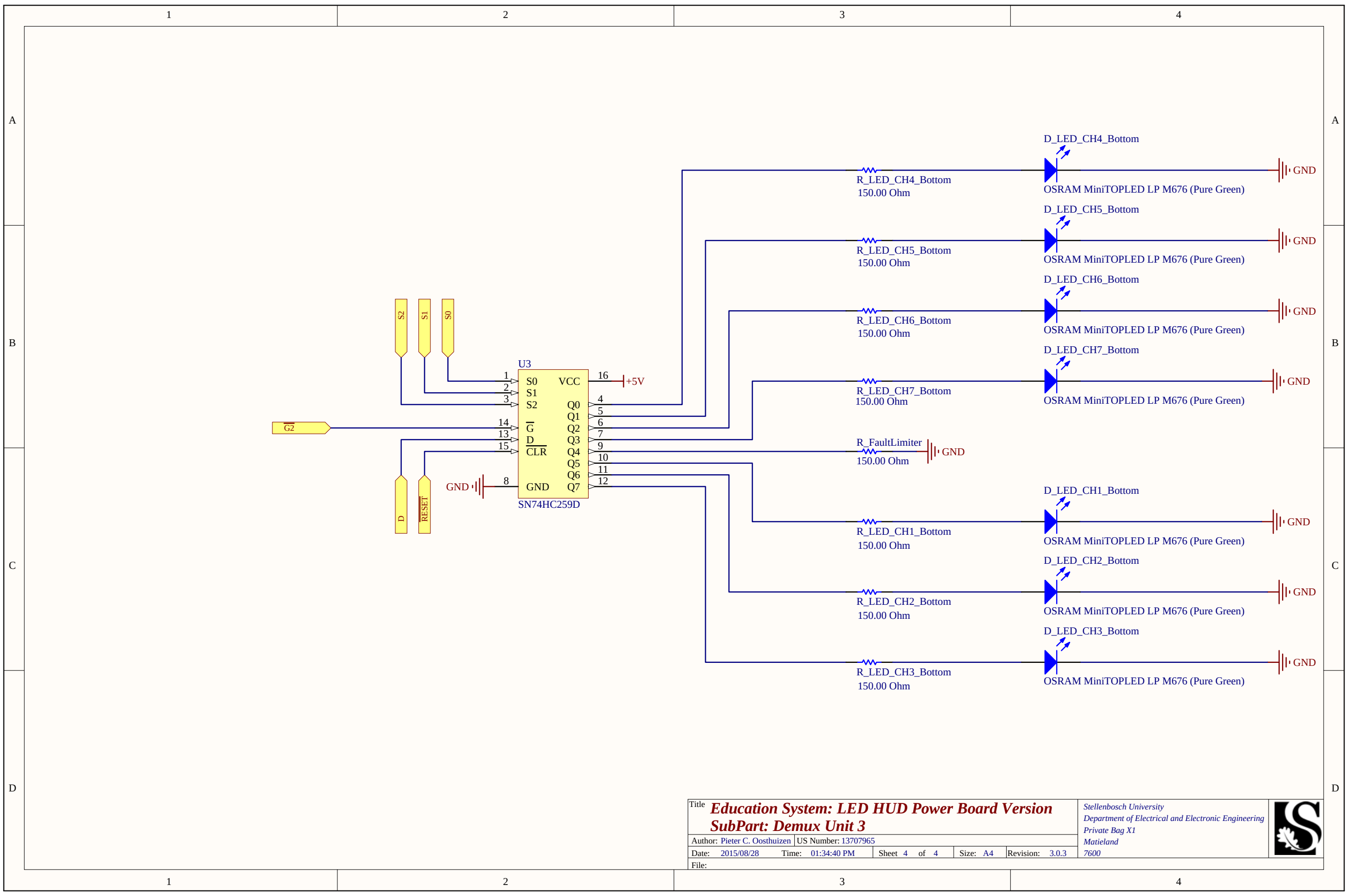

J_ACSup_MeasOut
J_ACSup_MeasIn
J_SupplyInput
J_CH7_PowerPlug
J_CH6_PowerPlug
J_CH5_PowerPlug
J_CH4_PowerPlug
J_CH3_PowerPlug
J_CH2_PowerPlug
J_CH1_PowerPlug
Channel 7
Channel 6
Channel 5
Channel 4
Channel 3
Channel 2
Channel 1
WARNING
LETHAL VOLTAGES AND CURRENTS. USE EXTREME CAUTION.

C.2 Prototype Three: LED Front-Panel for AC Power Supply Module




Education System: LED HUD Power Board Version
SubPart: Demux Unit 1
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:34:39 PM
Sheet 2 of 4
Size: A4
Revision: 3.0.3
Stellenbosch University
Department of Electrical and Electronic Engineering
Private Bag X1
Matieland
7600
U1
SN74HC259D
D_LED_CH4_Top
R_LED_CH4_Top
150.00 Ohm
OSRAM MiniTOPLED LS M676 (Super Red)
D_LED_PWR
R_LED_PWR
OSRAM MiniTOPLED LW M673 (White)
GND
+5V


Education System: LED HUD Power Board Version
SubPart: Demux Unit 2
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:34:39 PM
Sheet 3 of 4
Size: A4
Revision: 3.0.3
Stellenbosch University
Department of Electrical and Electronic Engineering
Private Bag X1
Matieland
7600
U2
SN74HC259D
D_LED_CH4_Center
R_LED_CH4_Center
150.00 Ohm
OSRAM MiniTOPLED LY M676 (Yellow)
D_LED_LAN
R_LED_LAN
OSRAM MiniTOPLED LB M673 (Blue)
GND
+5V


D_LED_CH4_Bottom
R_LED_CH4_Bottom
150.00 Ohm
OSRAM MiniTOPLED LP M676 (Pure Green)
GND
U3
SN74HC259D
R_FaultLimiter
150.00 Ohm
Education System: LED HUD Power Board Version
SubPart: Demux Unit 3
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:34:40 PM
Sheet 4 of 4
Size: A4
Revision: 3.0.3
Stellenbosch University
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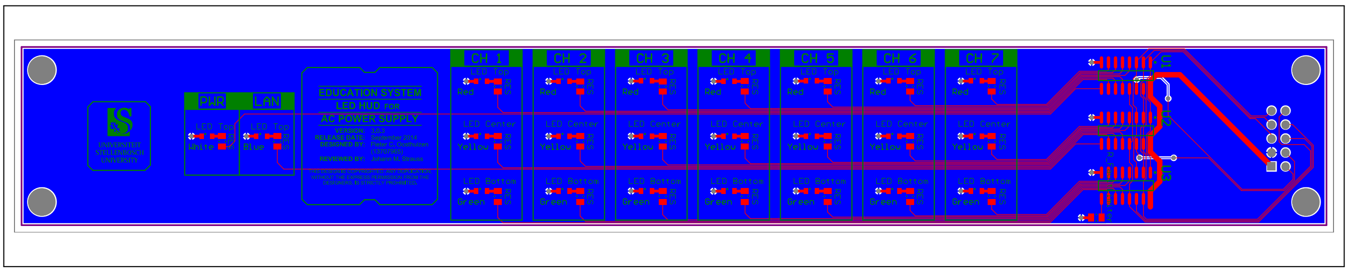
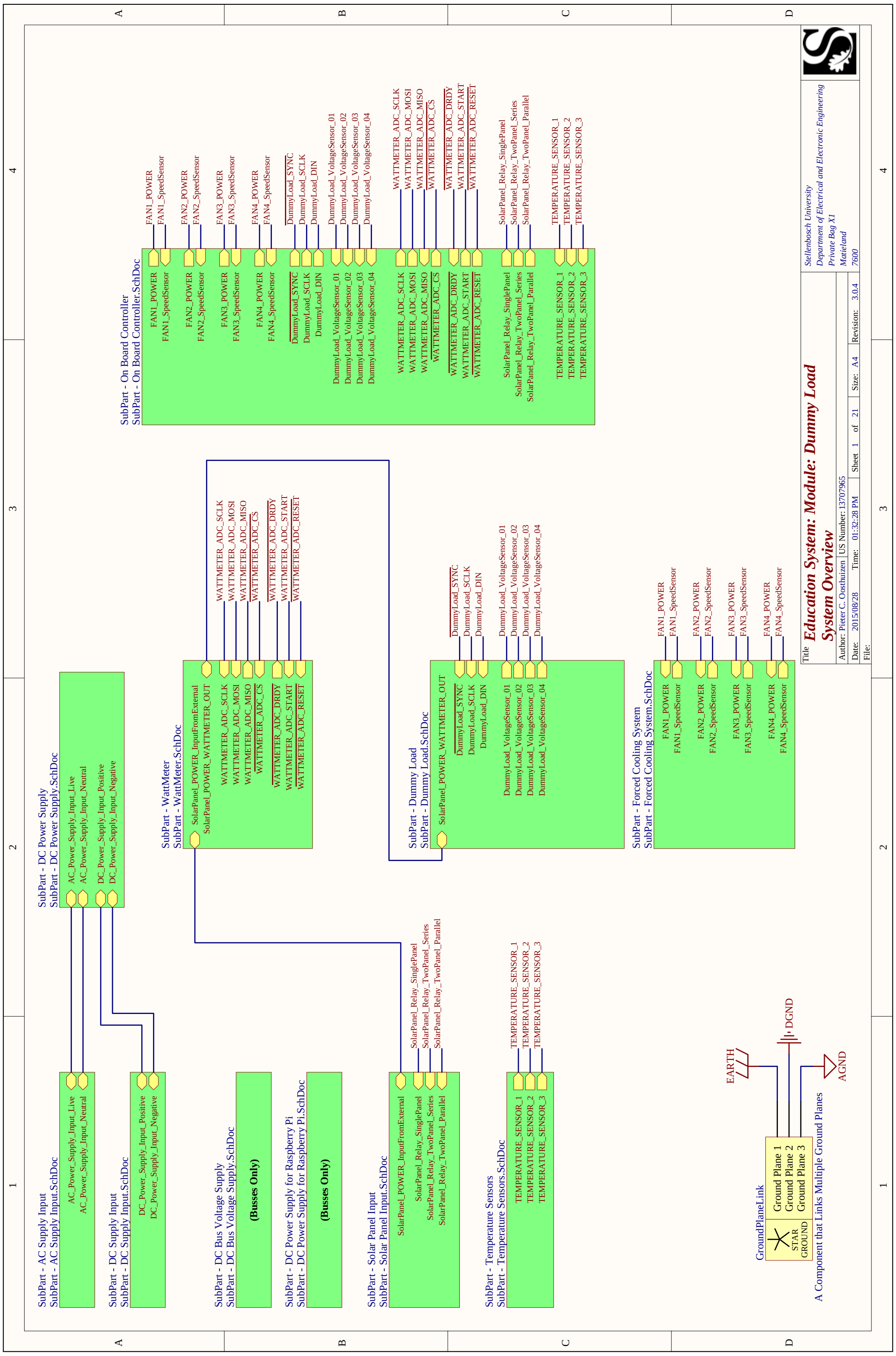
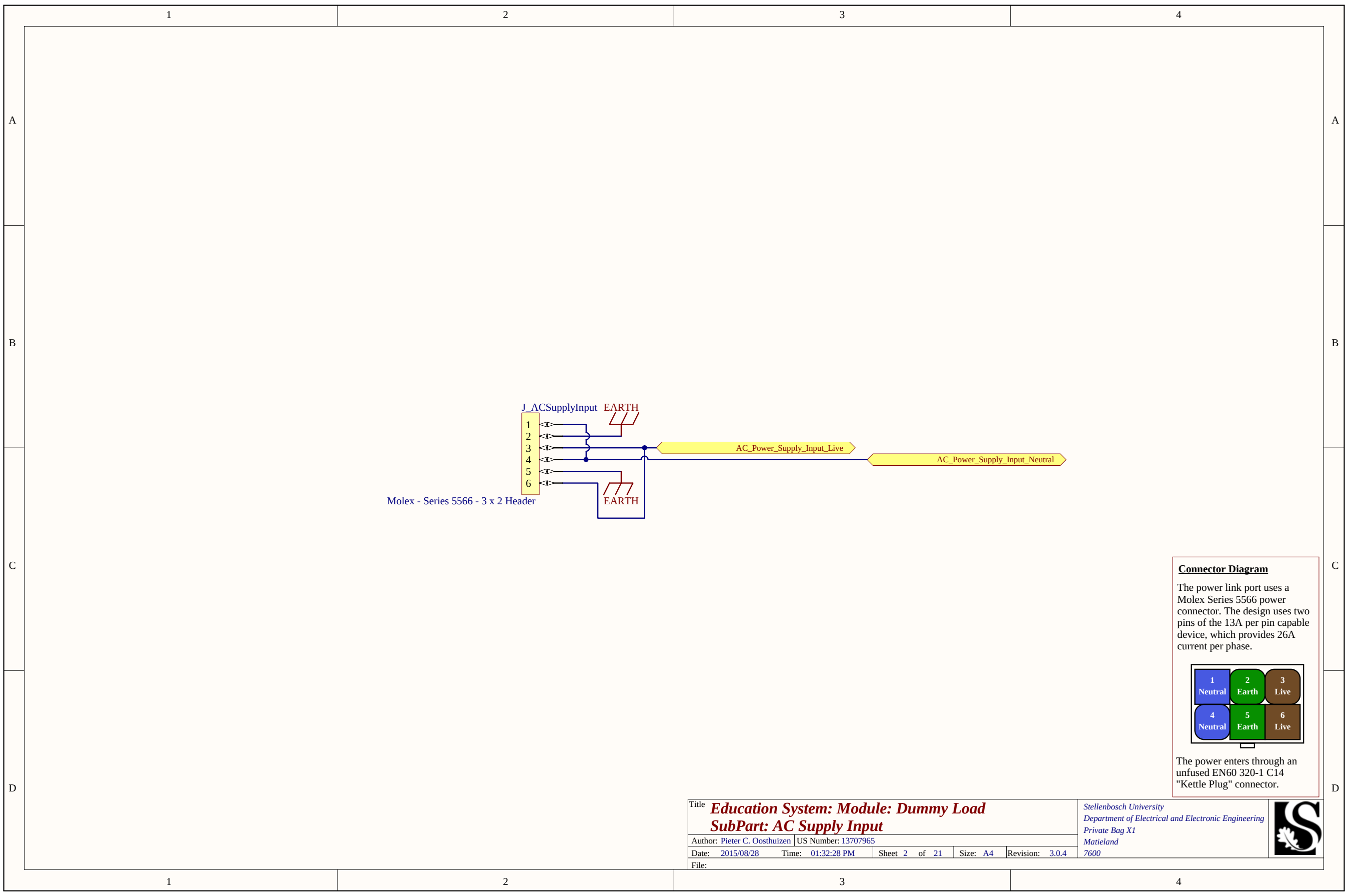

CH 1
CH 2
CH 3
CH 4
CH 5
CH 6
CH 7
PWR
LAN
EDUCATION SYSTEM
LED HUD FOR
AC POWER SUPPLY

C.3 Prototype Three: Solar Photovoltaic Dummy Load Experiment Module




J_ACSupplyInput
EARTH
Molex - Series 5566 - 3 x 2 Header
AC_Power_Supply_Input_Live
AC_Power_Supply_Input_Neutral
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
1 Neutral
2 Earth
3 Live
4 Neutral
5 Earth
6 Live
The power enters through an unfused EN60 320-1 C14 "Kettle Plug" connector.
Education System: Module: Dummy Load
SubPart: AC Supply Input
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 2 of 21
Size: A4
Revision: 3.0.4
File:
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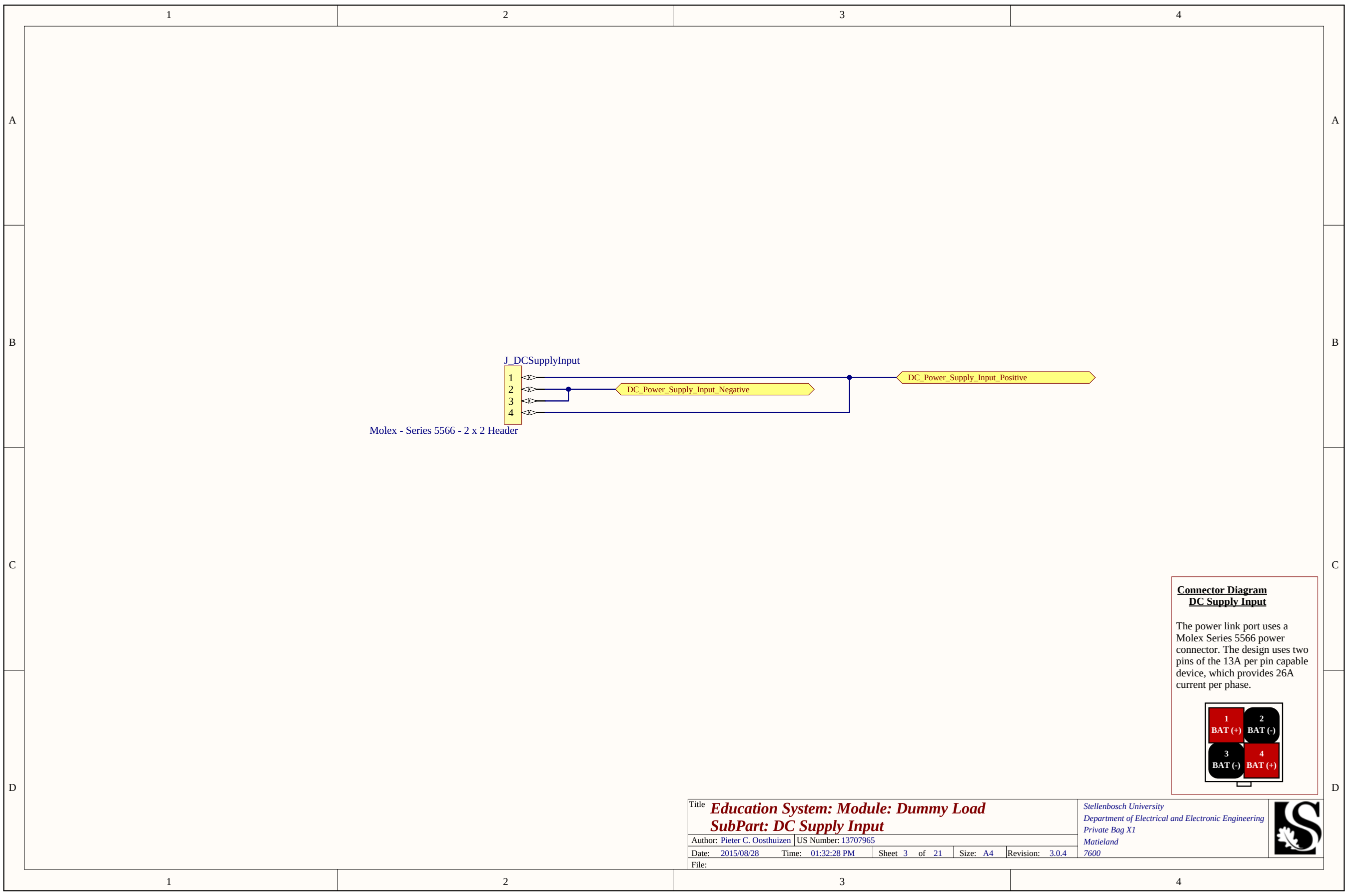
J_DCSupplyInput
Molex - Series 5566 - 2 x 2 Header
DC_Power_Supply_Input_Negative
DC_Power_Supply_Input_Positive
Connector Diagram
DC Supply Input
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
1 BAT (+)
2 BAT (-)
3 BAT (-)
4 BAT (+)
Education System: Module: Dummy Load
SubPart: DC Supply Input
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 3 of 21
Size: A4
Revision: 3.0.4
File:
Stellenbosch University
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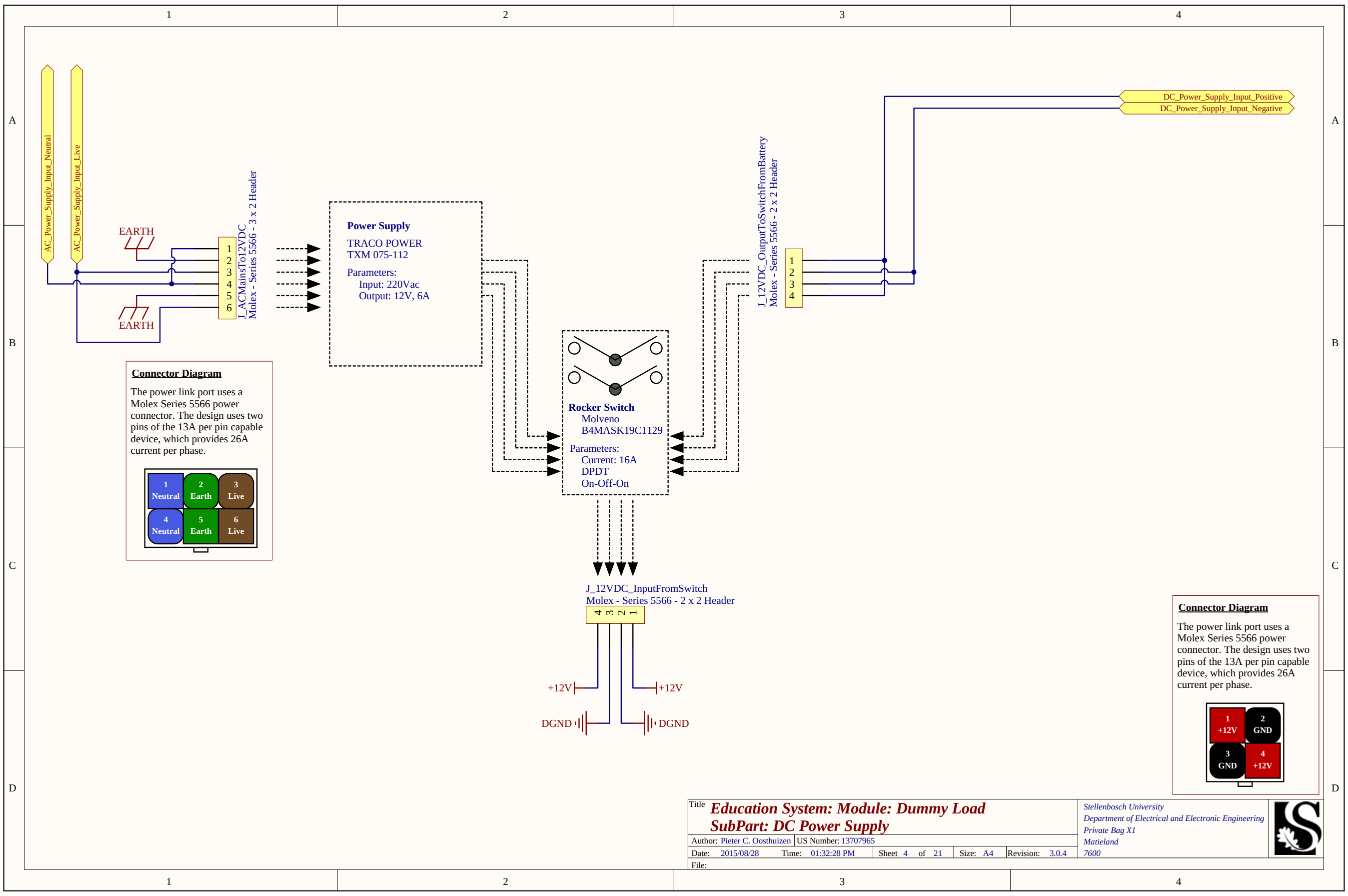
AC_Power_Supply_Input_Neutral
AC_Power_Supply_Input_Live
EARTH
J_ACMainsTo12VDC
Molex - Series 5566 - 3 x 2 Header
Power Supply
TRACO POWER
TXM 075-112
Parameters:
Input: 220Vac
Output: 12V, 6A
Connector Diagram
The power link port uses a Molex Series 5566 power connector. The design uses two pins of the 13A per pin capable device, which provides 26A current per phase.
1 Neutral
2 Earth
3 Live
4 Neutral
5 Earth
6 Live
Rocker Switch
Molveno
B4MASK19C1129
Parameters:
Current: 16A
DPDT
On-Off-On
J_12VDC_OutputToSwitchFromBattery
Molex - Series 5566 - 2 x 2 Header
DC_Power_Supply_Input_Positive
DC_Power_Supply_Input_Negative
J_12VDC_InputFromSwitch
Molex - Series 5566 - 2 x 2 Header
+12V
DGND
1 +12V
2 GND
3 GND
4 +12V
Title Education System: Module: Dummy Load
SubPart: DC Power Supply
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 4 of 21
Size: A4
Revision: 3.0.4
File:
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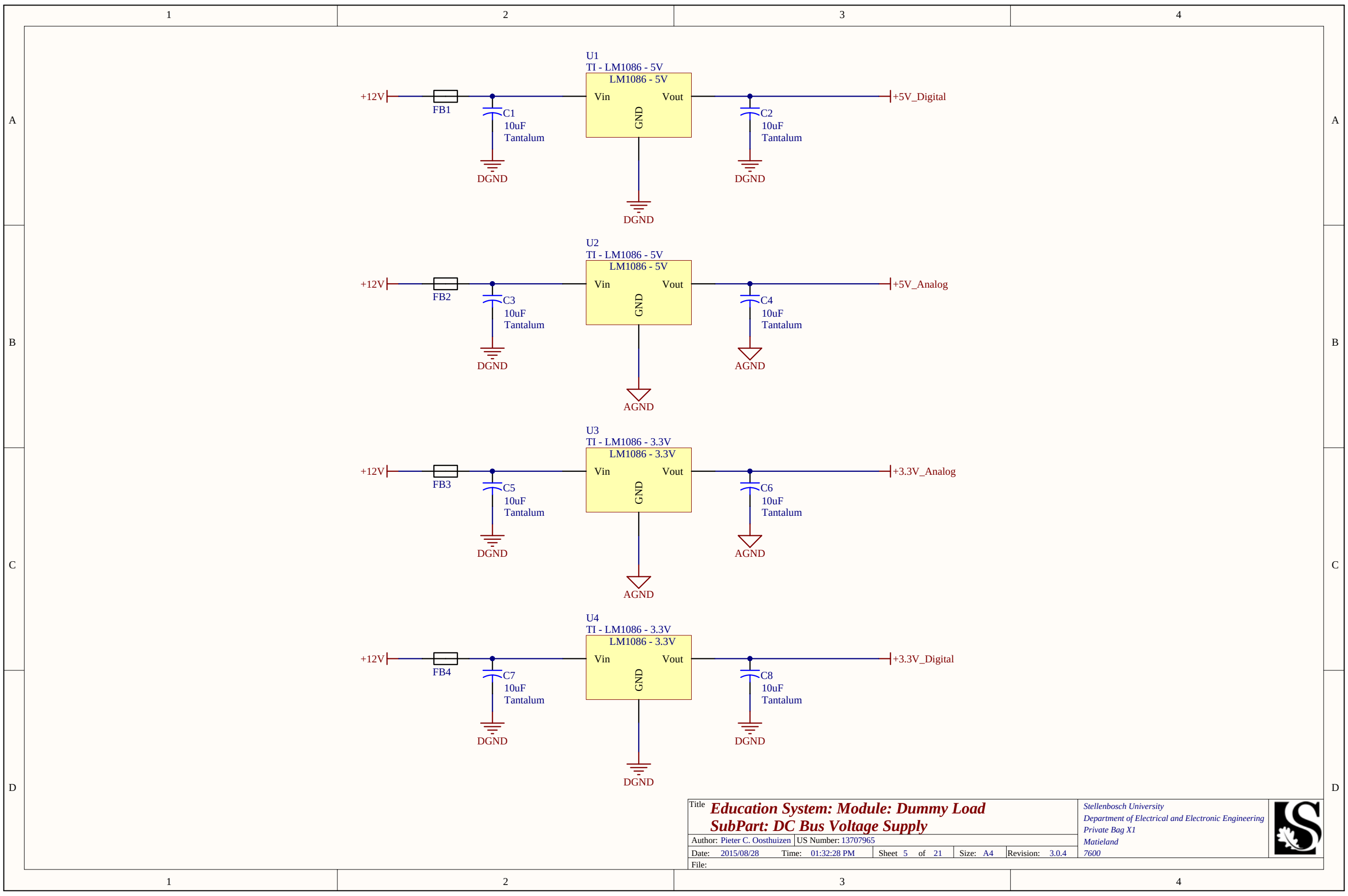
U1
TI - LM1086 - 5V
LM1086 - 5V
Vin
Vout
GND
+12V
FB1
C1
10uF
Tantalum
C2
DGND
+5V_Digital
U2
TI - LM1086 - 5V
FB2
C3
C4
AGND
+5V_Analog
U3
TI - LM1086 - 3.3V
LM1086 - 3.3V
FB3
C5
C6
+3.3V_Analog
U4
TI - LM1086 - 3.3V
FB4
C7
C8
+3.3V_Digital
Title Education System: Module: Dummy Load
SubPart: DC Bus Voltage Supply
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 5 of 21
Size: A4
Revision: 3.0.4
File:
Stellenbosch University
Department of Electrical and Electronic Engineering
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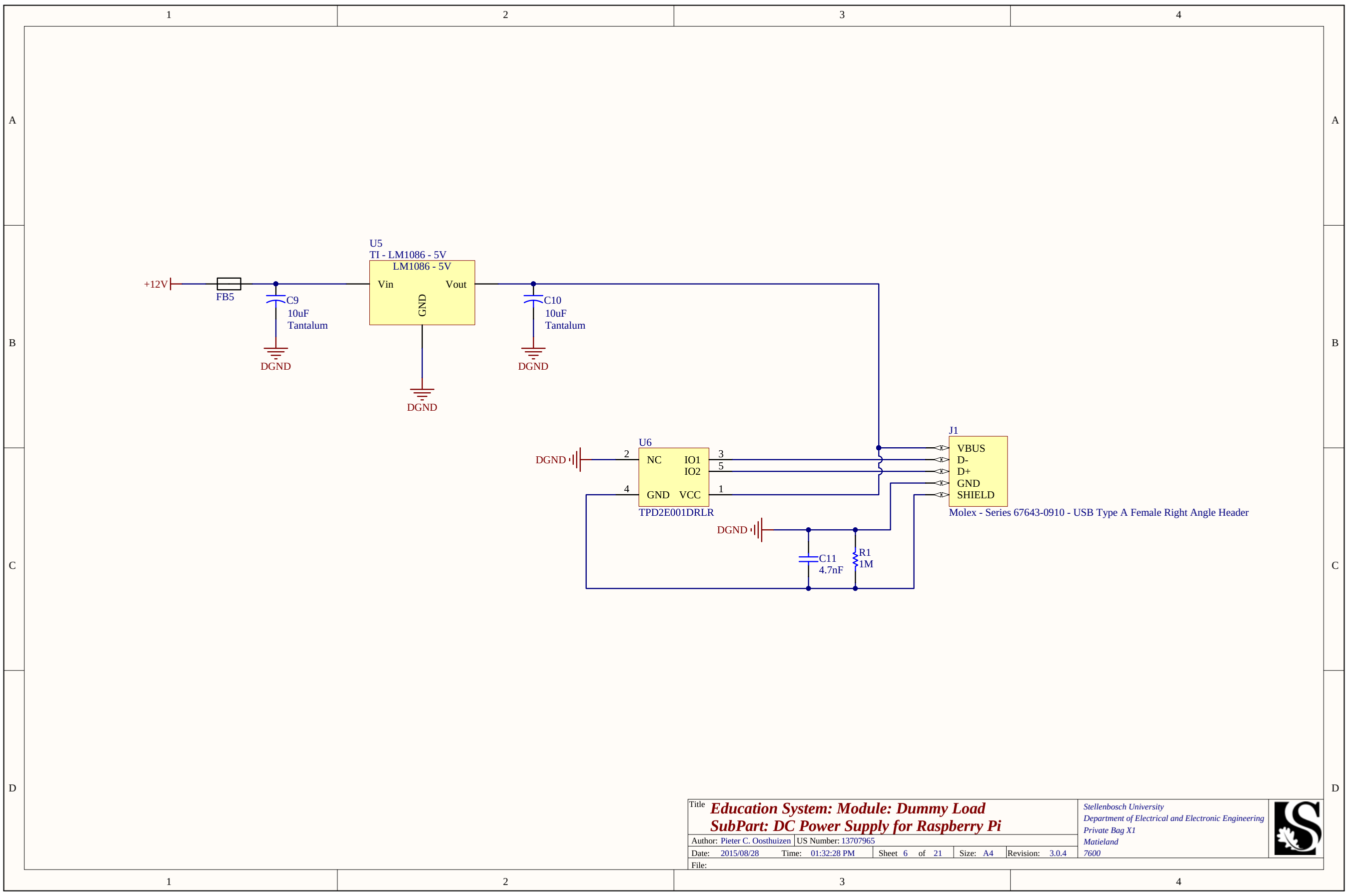
U5
TI - LM1086 - 5V
LM1086 - 5V
Vin
Vout
GND
+12V
FB5
C9
10uF
Tantalum
C10
10uF
Tantalum
DGND
U6
NC
IO1
IO2
GND
VCC
TPD2E001DRLR
J1
VBUS
D-
D+
GND
SHIELD
Molex - Series 67643-0910 - USB Type A Female Right Angle Header
C11
4.7nF
R1
1M
Education System: Module: Dummy Load
SubPart: DC Power Supply for Raspberry Pi
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 6 of 21
Size: A4
Revision: 3.0.4
File:
Stellenbosch University
Department of Electrical and Electronic Engineering
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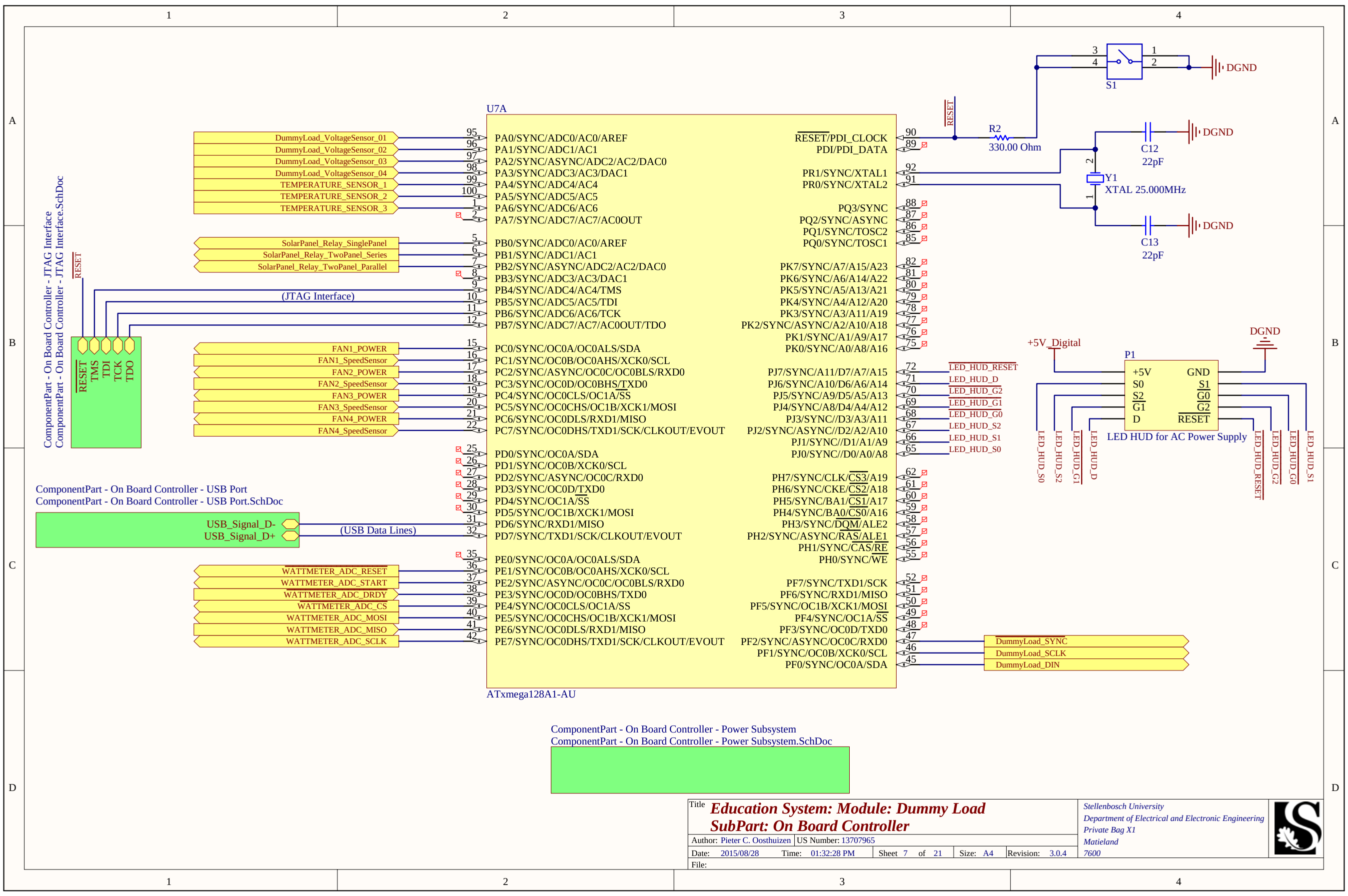
U7A
ATxmega128A1-AU
DummyLoad_VoltageSensor_01
DummyLoad_VoltageSensor_02
DummyLoad_VoltageSensor_03
DummyLoad_VoltageSensor_04
TEMPERATURE_SENSOR_1
TEMPERATURE_SENSOR_2
TEMPERATURE_SENSOR_3
SolarPanel_Relay_SinglePanel
SolarPanel_Relay_TwoPanel_Series
SolarPanel_Relay_TwoPanel_Parallel
(JTAG Interface)
FAN1_POWER
FAN1_SpeedSensor
FAN2_POWER
FAN2_SpeedSensor
FAN3_POWER
FAN3_SpeedSensor
FAN4_POWER
FAN4_SpeedSensor
ComponentPart - On Board Controller - JTAG Interface
ComponentPart - On Board Controller - JTAG Interface.SchDoc
RESET
TMS
TDI
TCK
TDO
ComponentPart - On Board Controller - USB Port
ComponentPart - On Board Controller - USB Port.SchDoc
USB_Signal_D-
USB_Signal_D+
(USB Data Lines)
WATTMETER_ADC_RESET
WATTMETER_ADC_START
WATTMETER_ADC_DRDY
WATTMETER_ADC_CS
WATTMETER_ADC_MOSI
WATTMETER_ADC_MISO
WATTMETER_ADC_SCLK
DummyLoad_SYNC
DummyLoad_SCLK
DummyLoad_DIN
S1
R2
330.00 Ohm
C12
22pF
C13
22pF
Y1
XTAL 25.000MHz
DGND
+5V_Digital
P1
LED HUD for AC Power Supply
LED_HUD_RESET
LED_HUD_D
LED_HUD_G2
LED_HUD_G1
LED_HUD_G0
LED_HUD_S2
LED_HUD_S1
LED_HUD_S0
ComponentPart - On Board Controller - Power Subsystem
ComponentPart - On Board Controller - Power Subsystem.SchDoc
Education System: Module: Dummy Load
SubPart: On Board Controller
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 7 of 21
Size: A4
Revision: 3.0.4
File:
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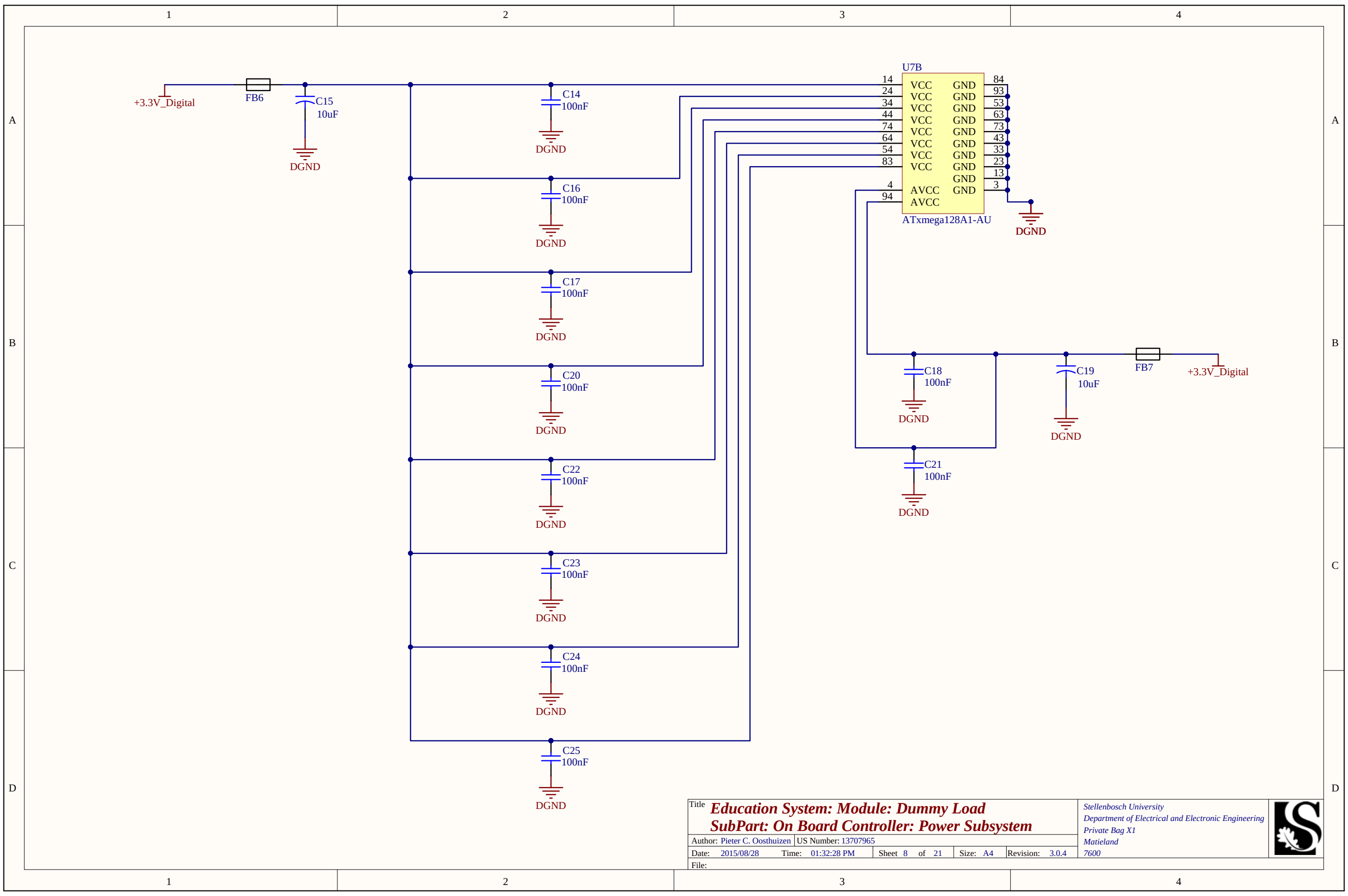

U7B
ATxmega128A1-AU
VCC
GND
AVCC
+3.3V_Digital
FB6
C15
10uF
DGND
C14
C16
C17
C20
C22
C23
C24
C25
100nF
C18
C19
C21
FB7
Education System: Module: Dummy Load
SubPart: On Board Controller: Power Subsystem
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 8 of 21
Size: A4
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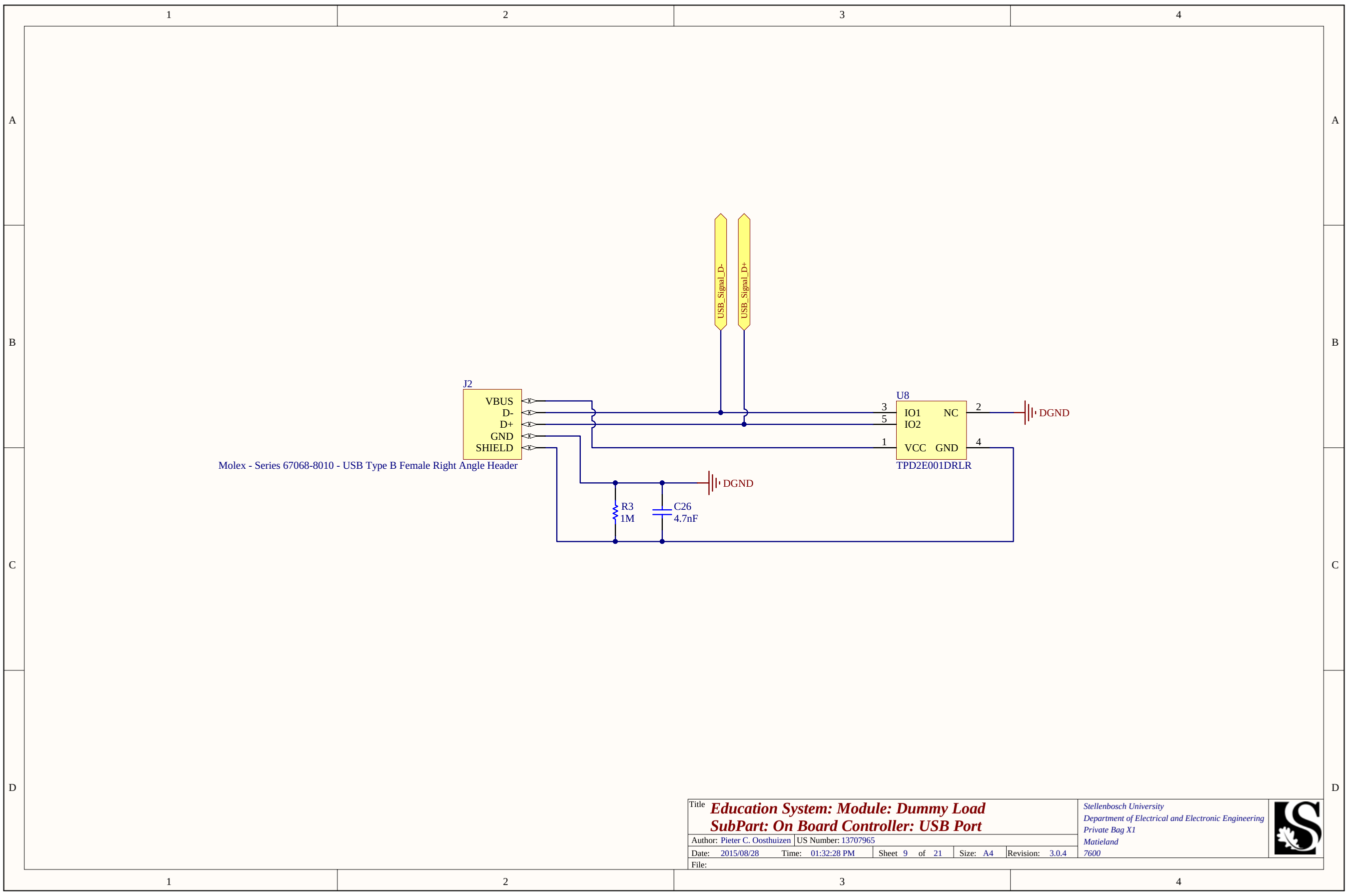

USB_Signal_D-
USB_Signal_D+
J2
VBUS
D-
D+
GND
SHIELD
Molex - Series 67068-8010 - USB Type B Female Right Angle Header
U8
IO1
IO2
NC
VCC
GND
TPD2E001DRLR
DGND
R3
1M
C26
4.7nF
Education System: Module: Dummy Load
SubPart: On Board Controller: USB Port
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 9 of 21
Size: A4
Revision: 3.0.4
Stellenbosch University
Department of Electrical and Electronic Engineering
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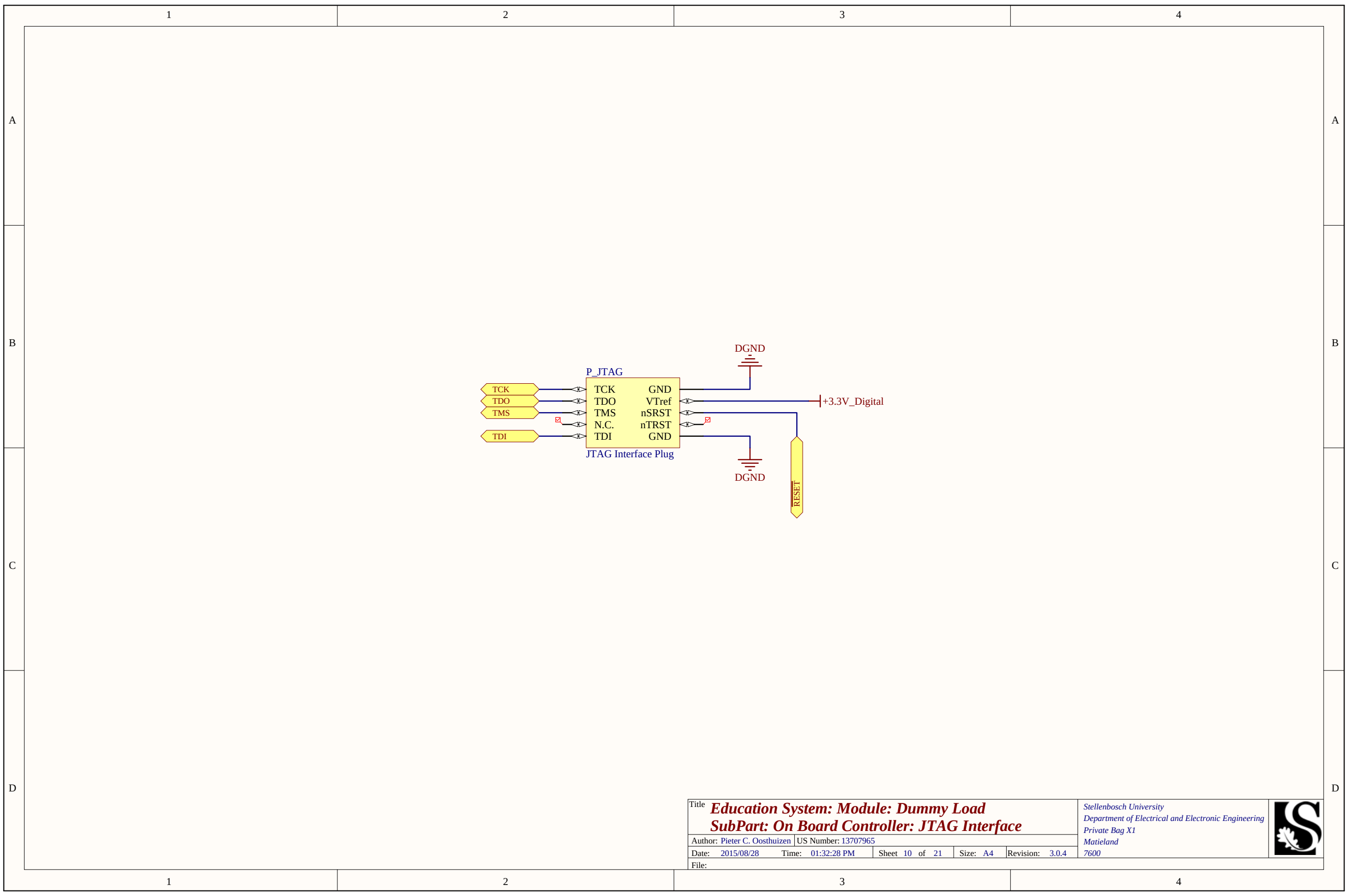
Matieland
7600



DGND
P_JTAG
TCK
TDO
TMS
TDI
TCK GND
TDO VTref
TMS nSRST
N.C. nTRST
TDI GND
+3.3V_Digital
JTAG Interface Plug
DGND
RESET
Education System: Module: Dummy Load
SubPart: On Board Controller: JTAG Interface
Author: Pieter C. Oosthuizen
US Number: 13707965
Date: 2015/08/28
Time: 01:32:28 PM
Sheet 10 of 21
Size: A4
Revision: 3.0.4
File:
Stellenbosch University
Department of Electrical and Electronic Engineering
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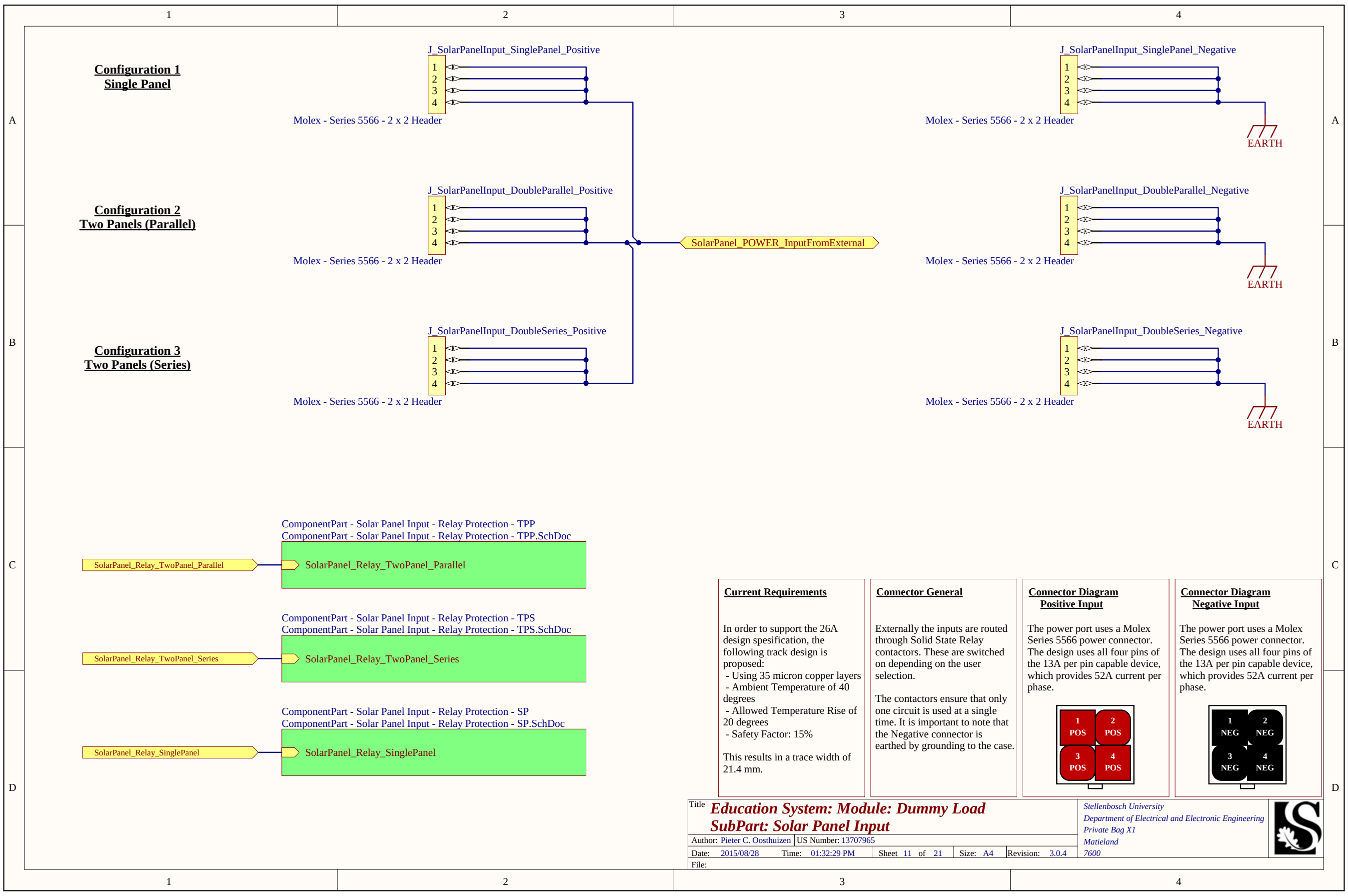
Matieland
7600



Configuration 1
Single Panel
J_SolarPanelInput_SinglePanel_Positive
Molex - Series 5566 - 2 x 2 Header
J_SolarPanelInput_SinglePanel_Negative
Molex - Series 5566 - 2 x 2 Header
EARTH
Configuration 2
Two Panels (Parallel)
J_SolarPanelInput_DoubleParallel_Positive
Molex - Series 5566 - 2 x 2 Header
SolarPanel_POWER_InputFromExternal
J_SolarPanelInput_DoubleParallel_Negative
Molex - Series 5566 - 2 x 2 Header
EARTH
Configuration 3
Two Panels (Series)
J_SolarPanelInput_DoubleSeries_Positive
Molex - Series 5566 - 2 x 2 Header
J_SolarPanelInput_DoubleSeries_Negative
Molex - Series 5566 - 2 x 2 Header
EARTH
ComponentPart - Solar Panel Input - Relay Protection - TPP
ComponentPart - Solar Panel Input - Relay Protection - TPP.SchDoc
SolarPanel_Relay_TwoPanel_Parallel
SolarPanel_Relay_TwoPanel_Parallel
ComponentPart - Solar Panel Input - Relay Protection - TPS
ComponentPart - Solar Panel Input - Relay Protection - TPS.SchDoc
SolarPanel_Relay_TwoPanel_Series
SolarPanel_Relay_TwoPanel_Series
ComponentPart - Solar Panel Input - Relay Protection - SP
ComponentPart - Solar Panel Input - Relay Protection - SP.SchDoc
SolarPanel_Relay_SinglePanel
SolarPanel_Relay_SinglePanel
Current Requirements
In order to support the 26A design spesification, the following track design is proposed:
- Using 35 micron copper layers
- Ambient Temperature of 40 degrees
- Allowed Temperature Rise of 20 degrees
- Safety Factor: 15%
This results in a trace width of 21.4 mm.
Connector General
Externally the inputs are routed through Solid State Relay contactors. These are switched on depending on the user selection.
The contactors ensure that only one circuit is used at a single time. It is important to note that the Negative connector is earthed by grounding to the case.
Connector Diagram
Positive Input
The power port uses a Molex Series 5566 power connector. The design uses all four pins of the 13A per pin capable device, which provides 52A current per phase.
1 POS
2 POS
3 POS
4 POS
Connector Diagram
Negative Input
The power port uses a Molex Series 5566 power connector. The design uses all four pins of the 13A per pin capable device, which provides 52A current per phase.
1 NEG
2 NEG
3 NEG
4 NEG
Education System: Module: Dummy Load
SubPart: Solar Panel Input
Author: Pieter C. Oosthuizen
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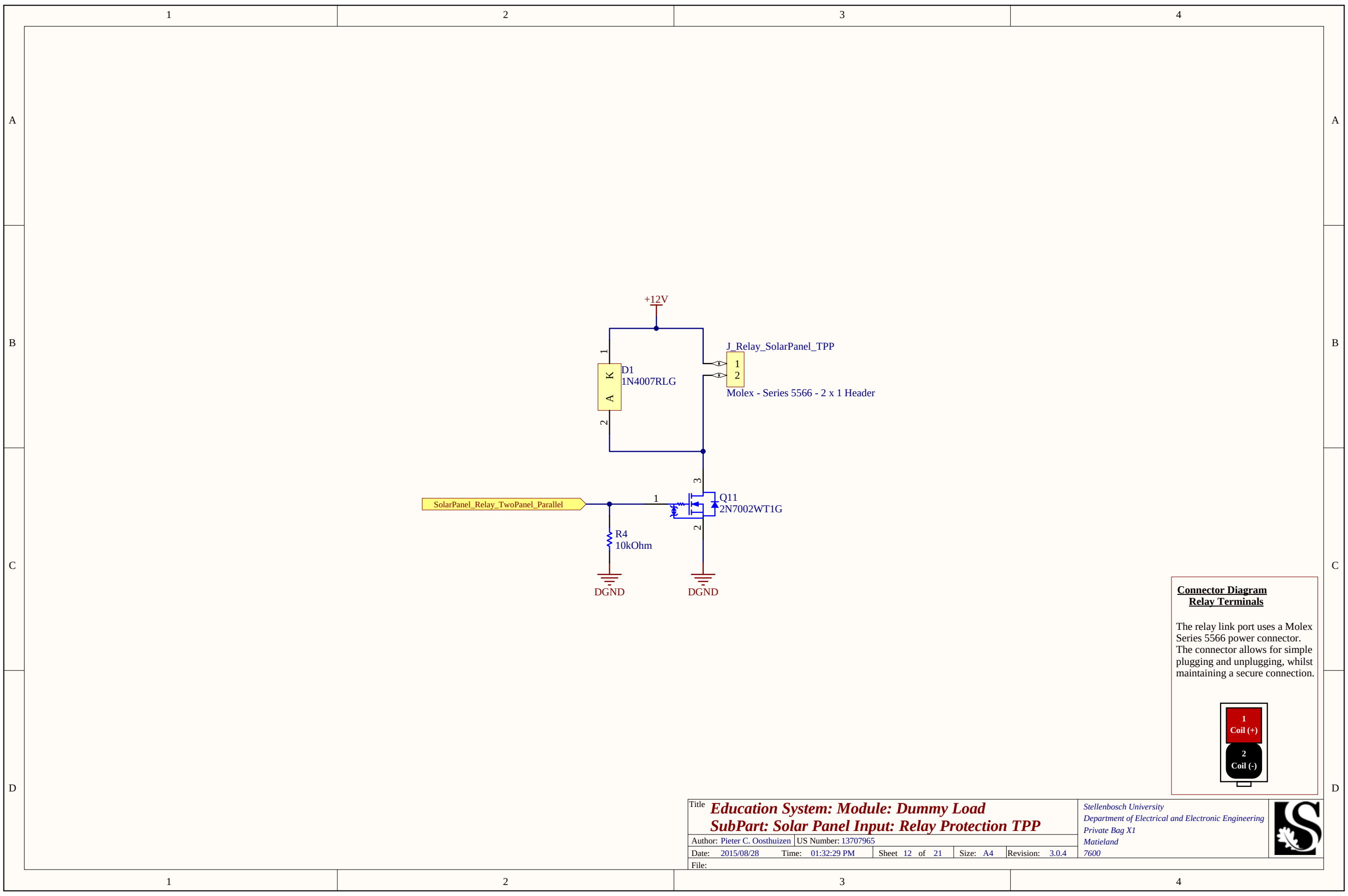

+12V
J_Relay_SolarPanel_TPP
D1
1N4007RLG
Molex - Series 5566 - 2 x 1 Header
SolarPanel_Relay_TwoPanel_Parallel
Q11
2N7002WT1G
R4
10kOhm
DGND
DGND
Connector Diagram
Relay Terminals
The relay link port uses a Molex Series 5566 power connector. The connector allows for simple plugging and unplugging, whilst maintaining a secure connection.
1 Coil (+)
2 Coil (-)
Education System: Module: Dummy Load
SubPart: Solar Panel Input: Relay Protection TPP
Author: Pieter C. Oosthuizen
US Number: 13707965
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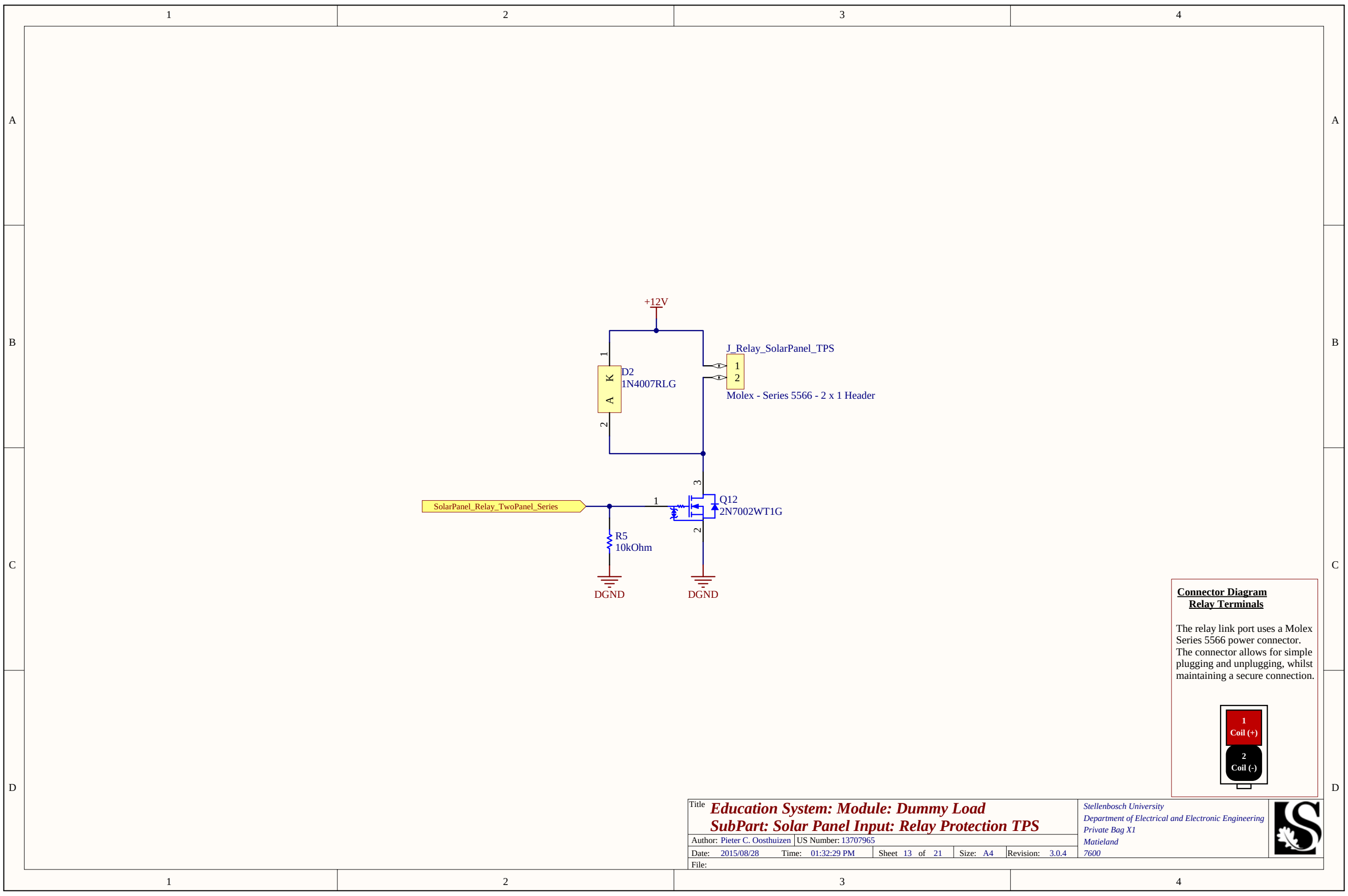

+12V
J_Relay_SolarPanel_TPS
D2
1N4007RLG
Molex - Series 5566 - 2 x 1 Header
SolarPanel_Relay_TwoPanel_Series
Q12
2N7002WT1G
R5
10kOhm
DGND
DGND
Connector Diagram
Relay Terminals
The relay link port uses a Molex Series 5566 power connector. The connector allows for simple plugging and unplugging, whilst maintaining a secure connection.
1 Coil (+)
2 Coil (-)
Education System: Module: Dummy Load
SubPart: Solar Panel Input: Relay Protection TPS
Author: Pieter C. Oosthuizen
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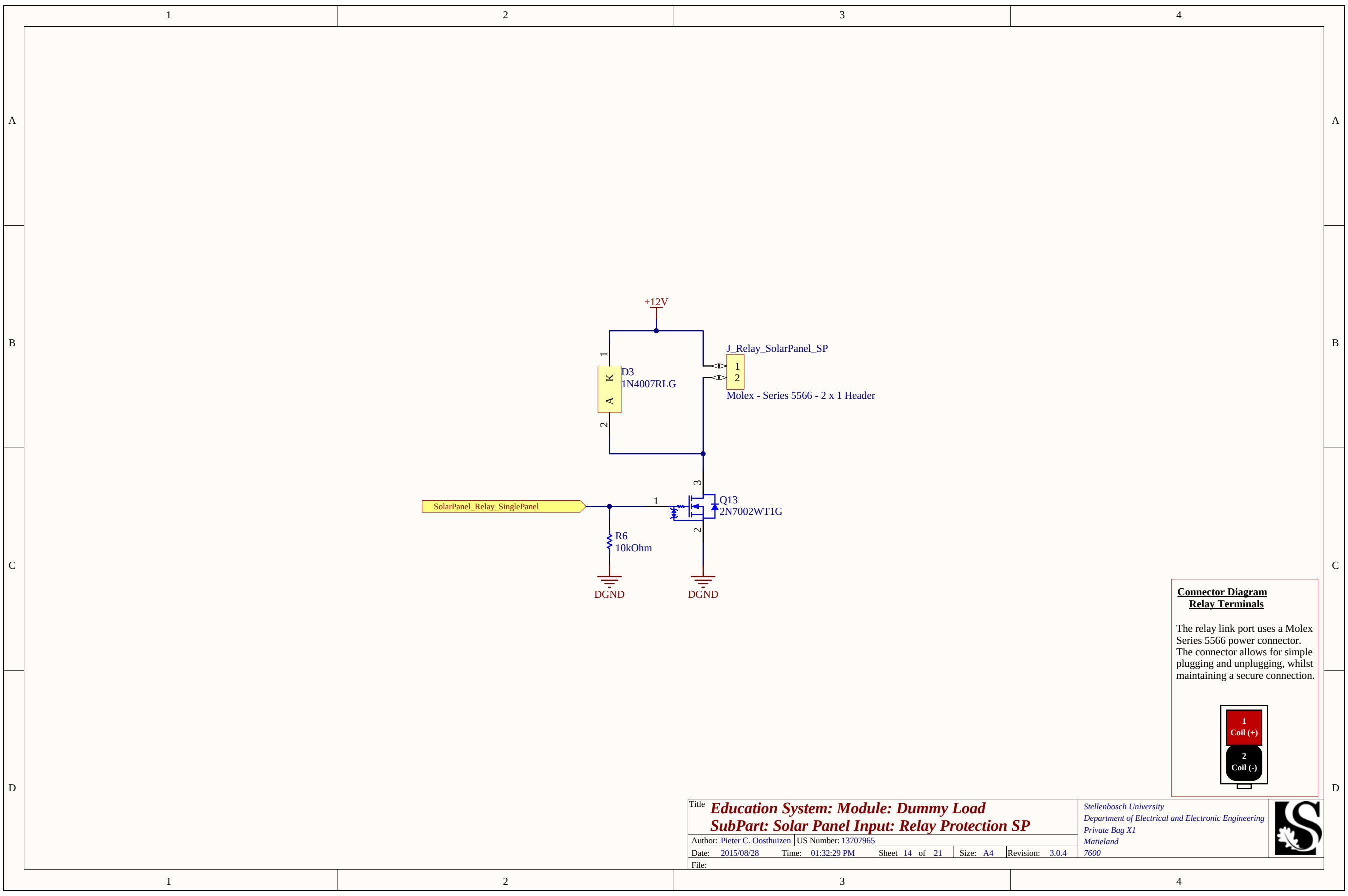
+12V
J_Relay_SolarPanel_SP
D3
1N4007RLG
Molex - Series 5566 - 2 x 1 Header
SolarPanel_Relay_SinglePanel
Q13
2N7002WT1G
R6
10kOhm
DGND
DGND
Connector Diagram
Relay Terminals
The relay link port uses a Molex Series 5566 power connector. The connector allows for simple plugging and unplugging, whilst maintaining a secure connection.
1 Coil (+)
2 Coil (-)
Education System: Module: Dummy Load
SubPart: Solar Panel Input: Relay Protection SP
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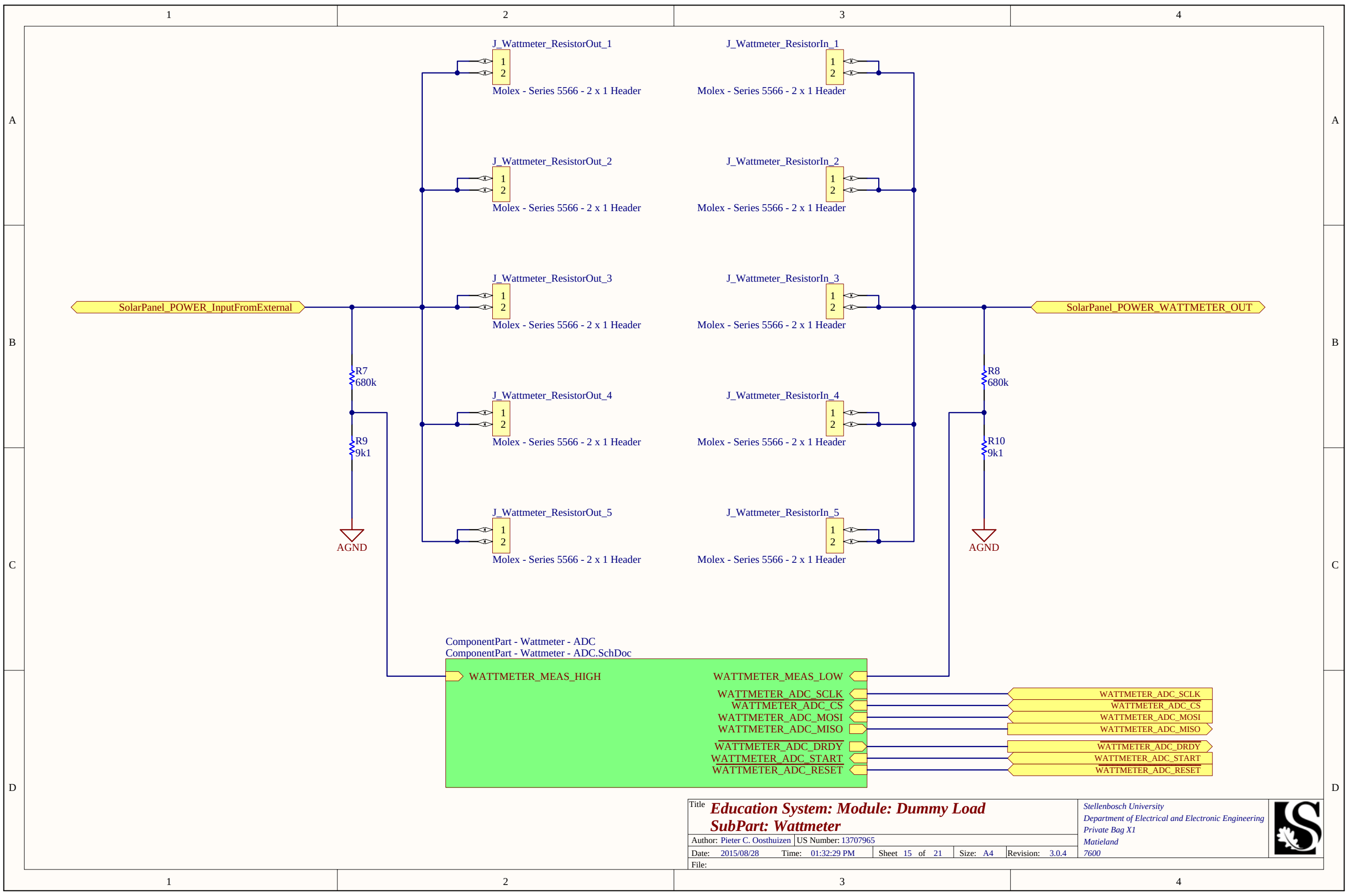
J_Wattmeter_ResistorOut_1
J_Wattmeter_ResistorIn_1
J_Wattmeter_ResistorOut_2
J_Wattmeter_ResistorIn_2
J_Wattmeter_ResistorOut_3
J_Wattmeter_ResistorIn_3
J_Wattmeter_ResistorOut_4
J_Wattmeter_ResistorIn_4
J_Wattmeter_ResistorOut_5
J_Wattmeter_ResistorIn_5
Molex - Series 5566 - 2 x 1 Header
SolarPanel_POWER_InputFromExternal
SolarPanel_POWER_WATTMETER_OUT
R7
680k
R9
9k1
R8
680k
R10
9k1
AGND
AGND
ComponentPart - Wattmeter - ADC
ComponentPart - Wattmeter - ADC.SchDoc
WATTMETER_MEAS_HIGH
WATTMETER_MEAS_LOW
WATTMETER_ADC_SCLK
WATTMETER_ADC_CS
WATTMETER_ADC_MOSI
WATTMETER_ADC_MISO
WATTMETER_ADC_DRDY
WATTMETER_ADC_START
WATTMETER_ADC_RESET
Education System: Module: Dummy Load
SubPart: Wattmeter
Author: Pieter C. Oosthuizen
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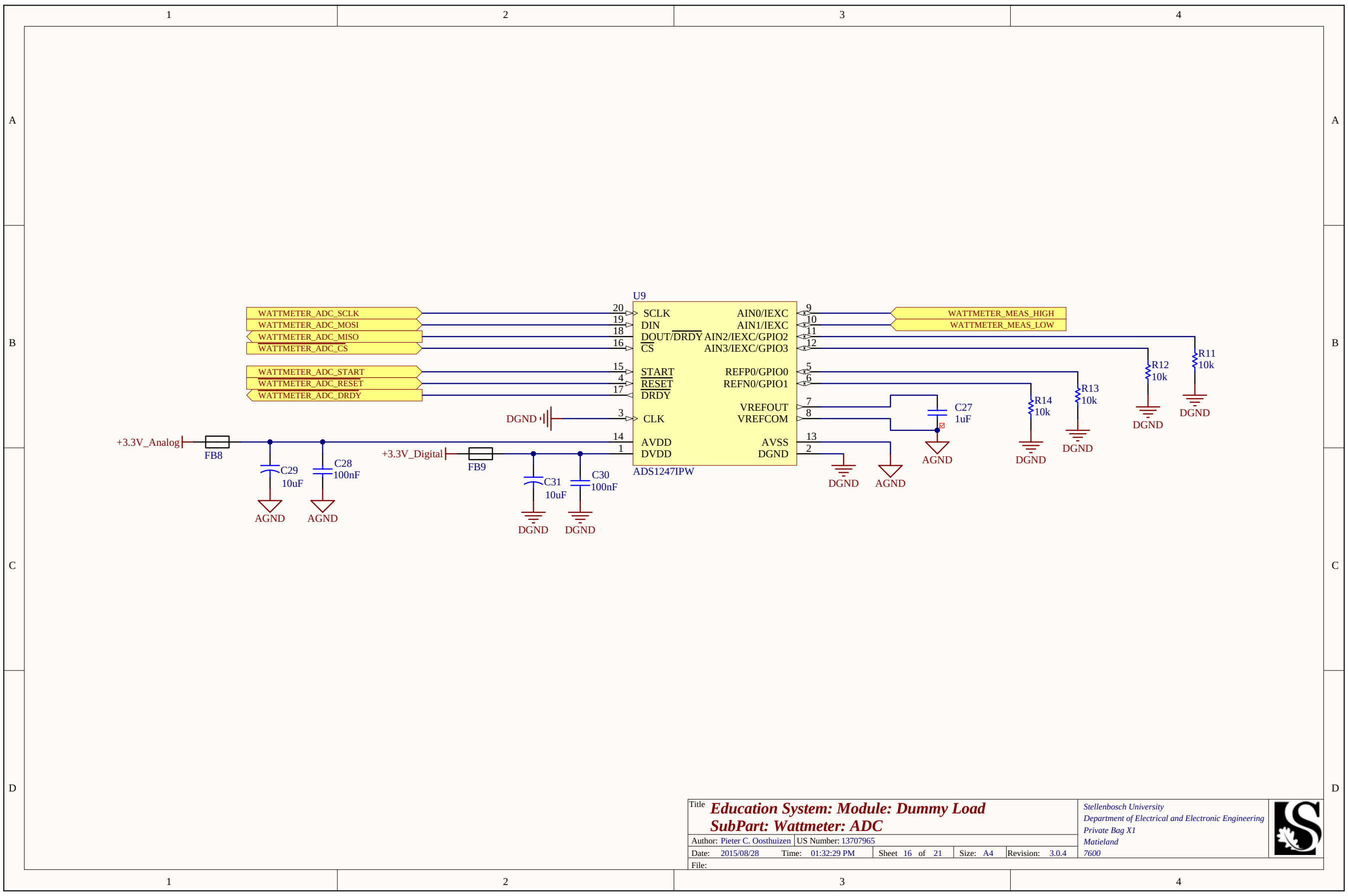
U9
SCLK
DIN
DOUT/DRDY
CS
START
RESET
DRDY
CLK
AVDD
DVDD
AIN0/IEXC
AIN1/IEXC
AIN2/IEXC/GPIO2
AIN3/IEXC/GPIO3
REFP0/GPIO0
REFN0/GPIO1
VREFOUT
VREFCOM
AVSS
DGND
ADS1247IPW
WATTMETER_ADC_SCLK
WATTMETER_ADC_MOSI
WATTMETER_ADC_MISO
WATTMETER_ADC_CS
WATTMETER_ADC_START
WATTMETER_ADC_RESET
WATTMETER_ADC_DRDY
WATTMETER_MEAS_HIGH
WATTMETER_MEAS_LOW
+3.3V_Analog
FB8
C29 10uF
C28 100nF
+3.3V_Digital
FB9
C31 10uF
C30 100nF
C27 1uF
R11 10k
R12 10k
R13 10k
R14 10k
AGND
DGND
Education System: Module: Dummy Load
SubPart: Wattmeter: ADC
Author: Pieter C. Oosthuizen
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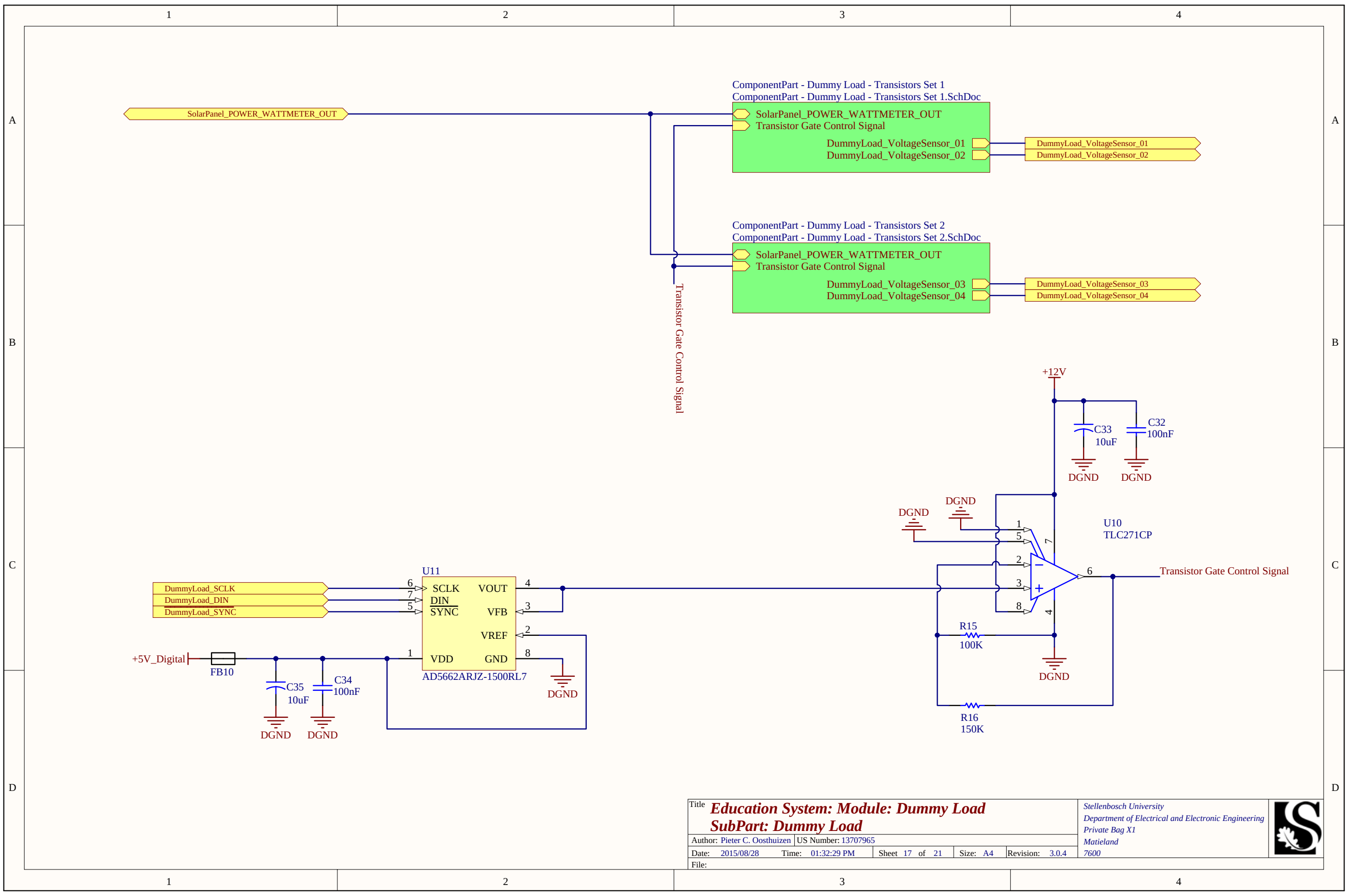
SolarPanel_POWER_WATTMETER_OUT
ComponentPart - Dummy Load - Transistors Set 1
ComponentPart - Dummy Load - Transistors Set 1.SchDoc
ComponentPart - Dummy Load - Transistors Set 2
ComponentPart - Dummy Load - Transistors Set 2.SchDoc
Transistor Gate Control Signal
DummyLoad_VoltageSensor_01
DummyLoad_VoltageSensor_02
DummyLoad_VoltageSensor_03
DummyLoad_VoltageSensor_04
+12V
C33 10uF
C32 100nF
U10
TLC271CP
R15 100K
R16 150K
U11
SCLK
DIN
SYNC
VDD
VOUT
VFB
VREF
GND
AD5662ARJZ-1500RL7
DummyLoad_SCLK
DummyLoad_DIN
DummyLoad_SYNC
+5V_Digital
FB10
C35 10uF
C34 100nF
DGND
Education System: Module: Dummy Load
SubPart: Dummy Load
Author: Pieter C. Oosthuizen
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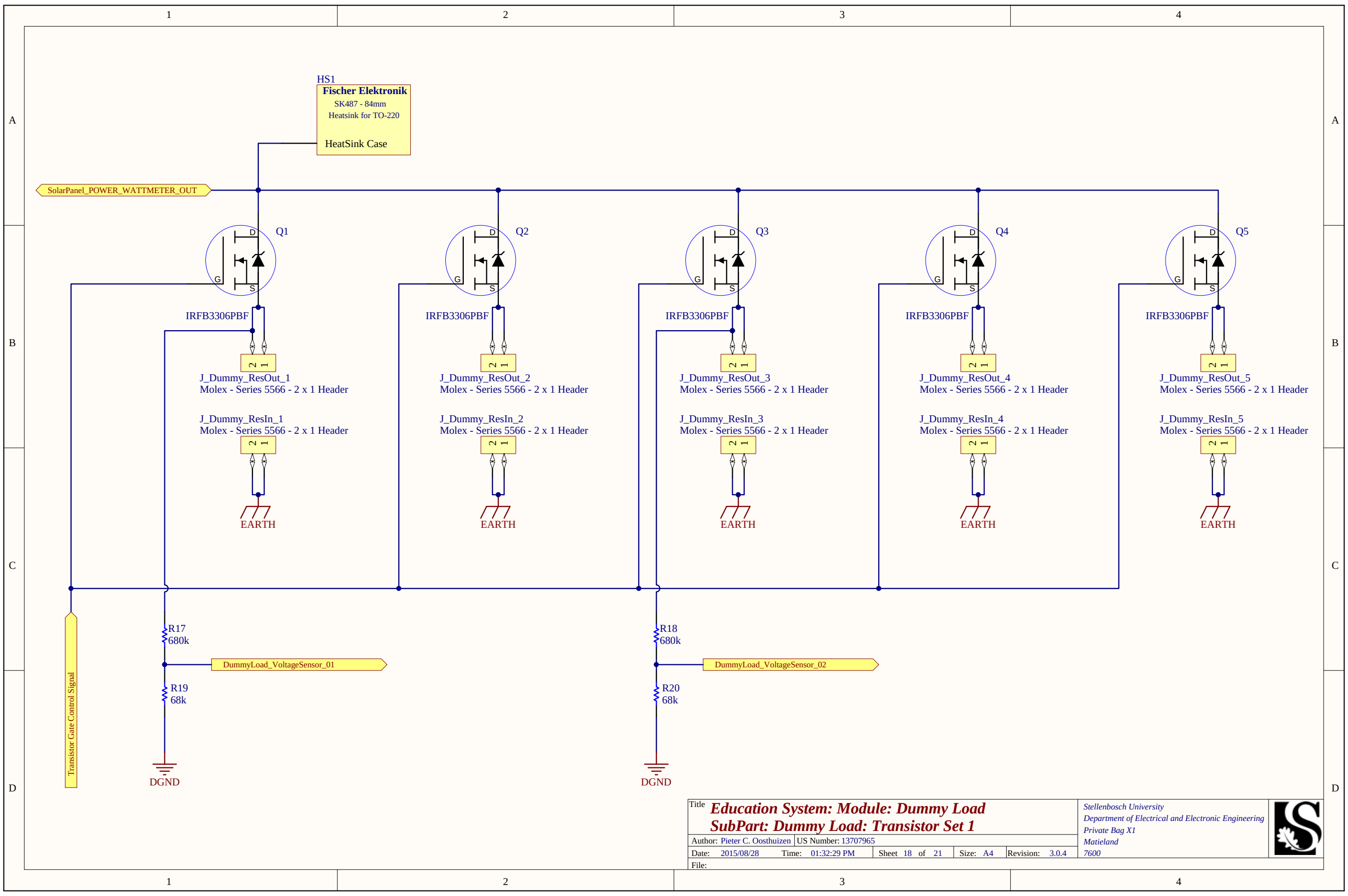
HS1
Fischer Elektronik
SK487 - 84mm
Heatsink for TO-220
HeatSink Case
SolarPanel_POWER_WATTMETER_OUT
Q1
Q2
Q3
Q4
Q5
IRFB3306PBF
J_Dummy_ResOut_1
Molex - Series 5566 - 2 x 1 Header
J_Dummy_ResIn_1
J_Dummy_ResOut_2
J_Dummy_ResIn_2
J_Dummy_ResOut_3
J_Dummy_ResIn_3
J_Dummy_ResOut_4
J_Dummy_ResIn_4
J_Dummy_ResOut_5
J_Dummy_ResIn_5
EARTH
R17
680k
R18
680k
DummyLoad_VoltageSensor_01
DummyLoad_VoltageSensor_02
R19
68k
R20
68k
Transistor Gate Control Signal
DGND
Education System: Module: Dummy Load
SubPart: Dummy Load: Transistor Set 1
Author: Pieter C. Oosthuizen
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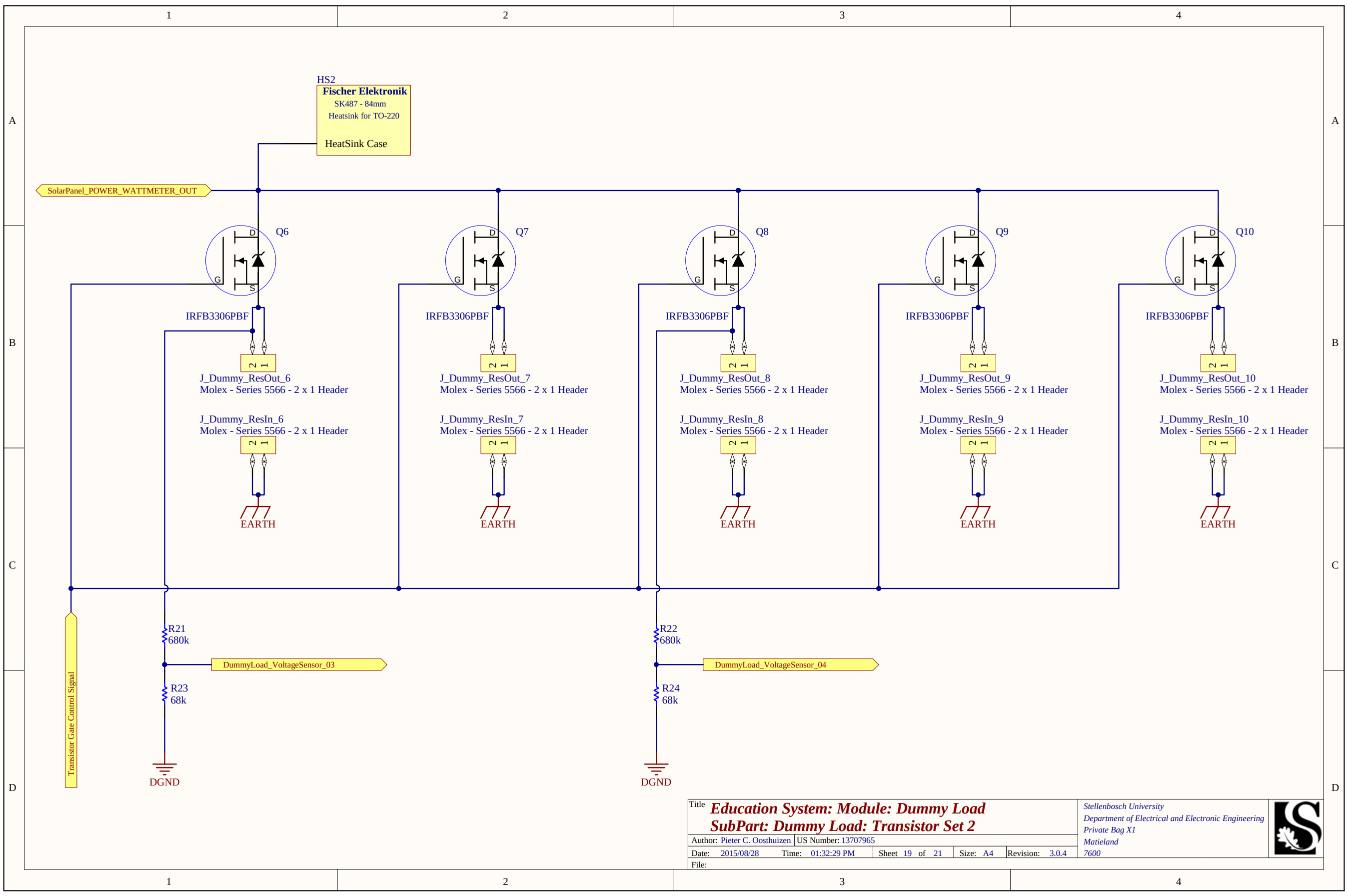
HS2
Fischer Elektronik
SK487 - 84mm
Heatsink for TO-220
HeatSink Case
SolarPanel_POWER_WATTMETER_OUT
Q6
Q7
Q8
Q9
Q10
IRFB3306PBF
J_Dummy_ResOut_6
Molex - Series 5566 - 2 x 1 Header
J_Dummy_ResIn_6
J_Dummy_ResOut_7
J_Dummy_ResIn_7
J_Dummy_ResOut_8
J_Dummy_ResIn_8
J_Dummy_ResOut_9
J_Dummy_ResIn_9
J_Dummy_ResOut_10
J_Dummy_ResIn_10
EARTH
R21
680k
R22
680k
DummyLoad_VoltageSensor_03
DummyLoad_VoltageSensor_04
R23
68k
R24
68k
Transistor Gate Control Signal
DGND
Education System: Module: Dummy Load
SubPart: Dummy Load: Transistor Set 2
Author: Pieter C. Oosthuizen
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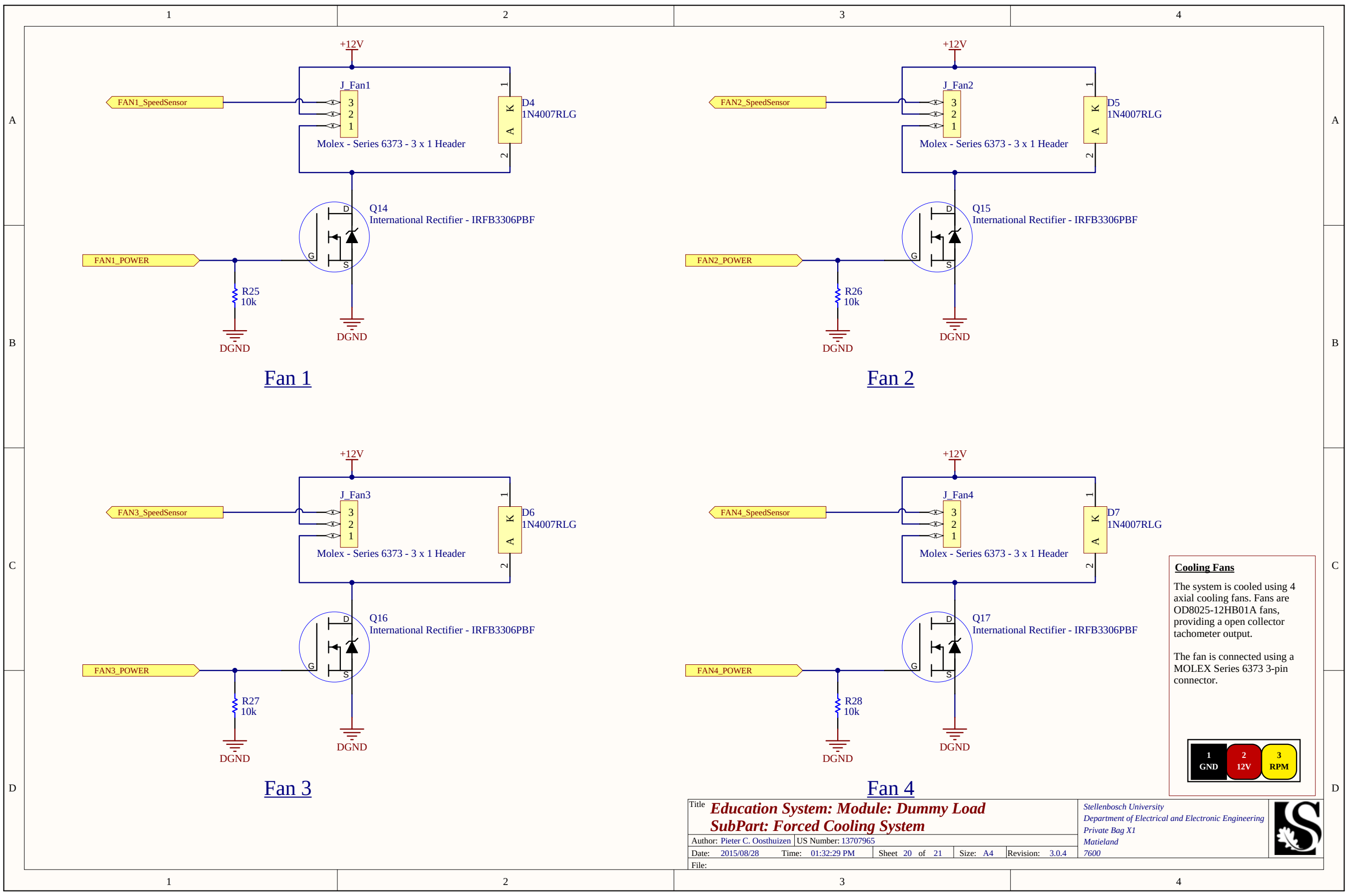

+12V
J_Fan1
FAN1_SpeedSensor
Molex - Series 6373 - 3 x 1 Header
D4
1N4007RLG
Q14
International Rectifier - IRFB3306PBF
FAN1_POWER
R25
10k
DGND
Fan 1
J_Fan2
FAN2_SpeedSensor
D5
Q15
FAN2_POWER
R26
Fan 2
J_Fan3
FAN3_SpeedSensor
D6
Q16
FAN3_POWER
R27
Fan 3
J_Fan4
FAN4_SpeedSensor
D7
Q17
FAN4_POWER
R28
Fan 4
Cooling Fans
The system is cooled using 4 axial cooling fans. Fans are OD8025-12HB01A fans, providing a open collector tachometer output.
The fan is connected using a MOLEX Series 6373 3-pin connector.
1 GND
2 12V
3 RPM
Title Education System: Module: Dummy Load
SubPart: Forced Cooling System
Author: Pieter C. Oosthuizen
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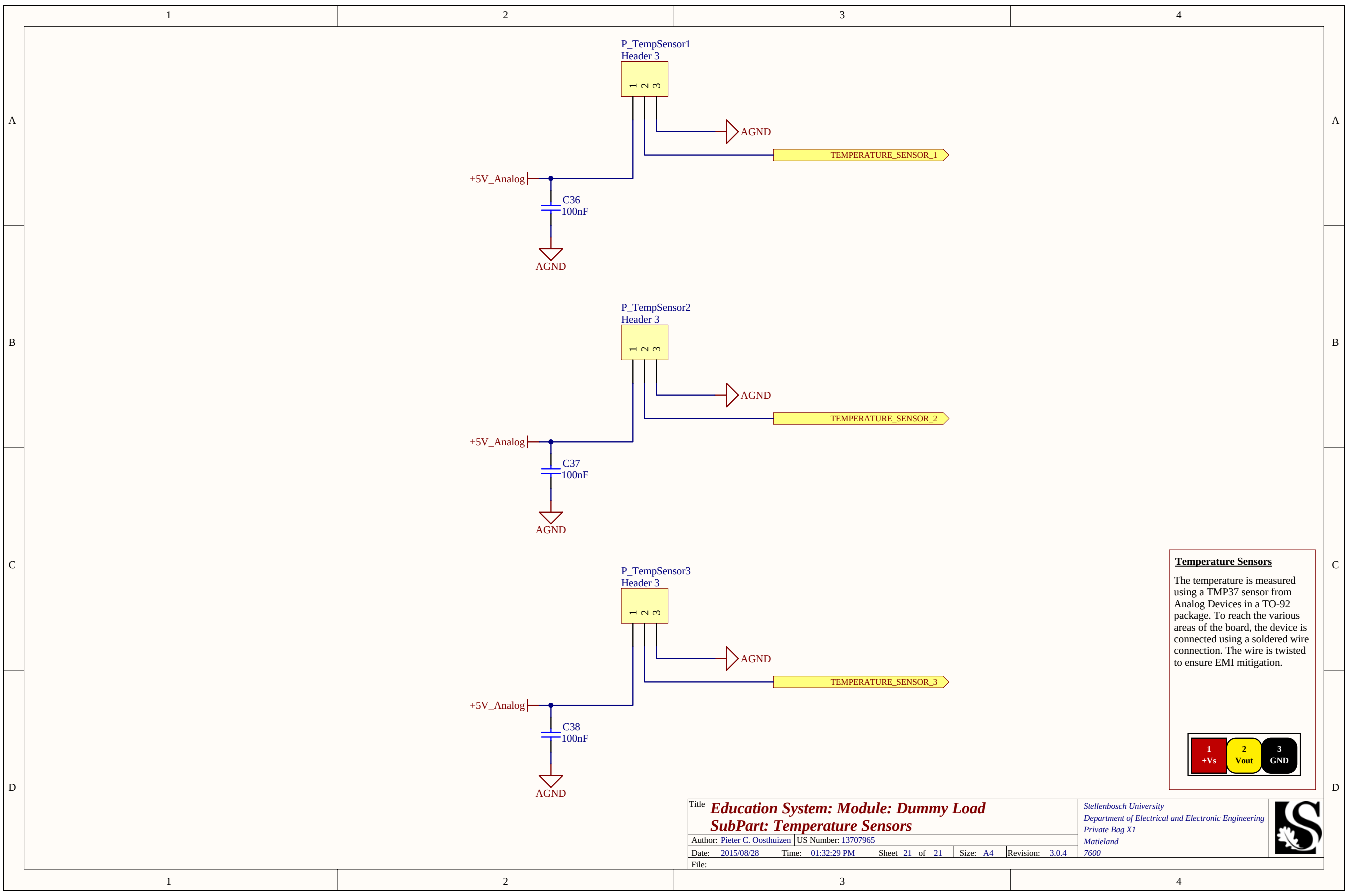

P_TempSensor1
Header 3
AGND
TEMPERATURE_SENSOR_1
+5V_Analog
C36
100nF
P_TempSensor2
Header 3
TEMPERATURE_SENSOR_2
C37
100nF
P_TempSensor3
Header 3
TEMPERATURE_SENSOR_3
C38
100nF
Temperature Sensors
The temperature is measured using a TMP37 sensor from Analog Devices in a TO-92 package. To reach the various areas of the board, the device is connected using a soldered wire connection. The wire is twisted to ensure EMI mitigation.
1 +Vs
2 Vout
3 GND
Title Education System: Module: Dummy Load
SubPart: Temperature Sensors
Author: Pieter C. Oosthuizen
US Number: 13707965
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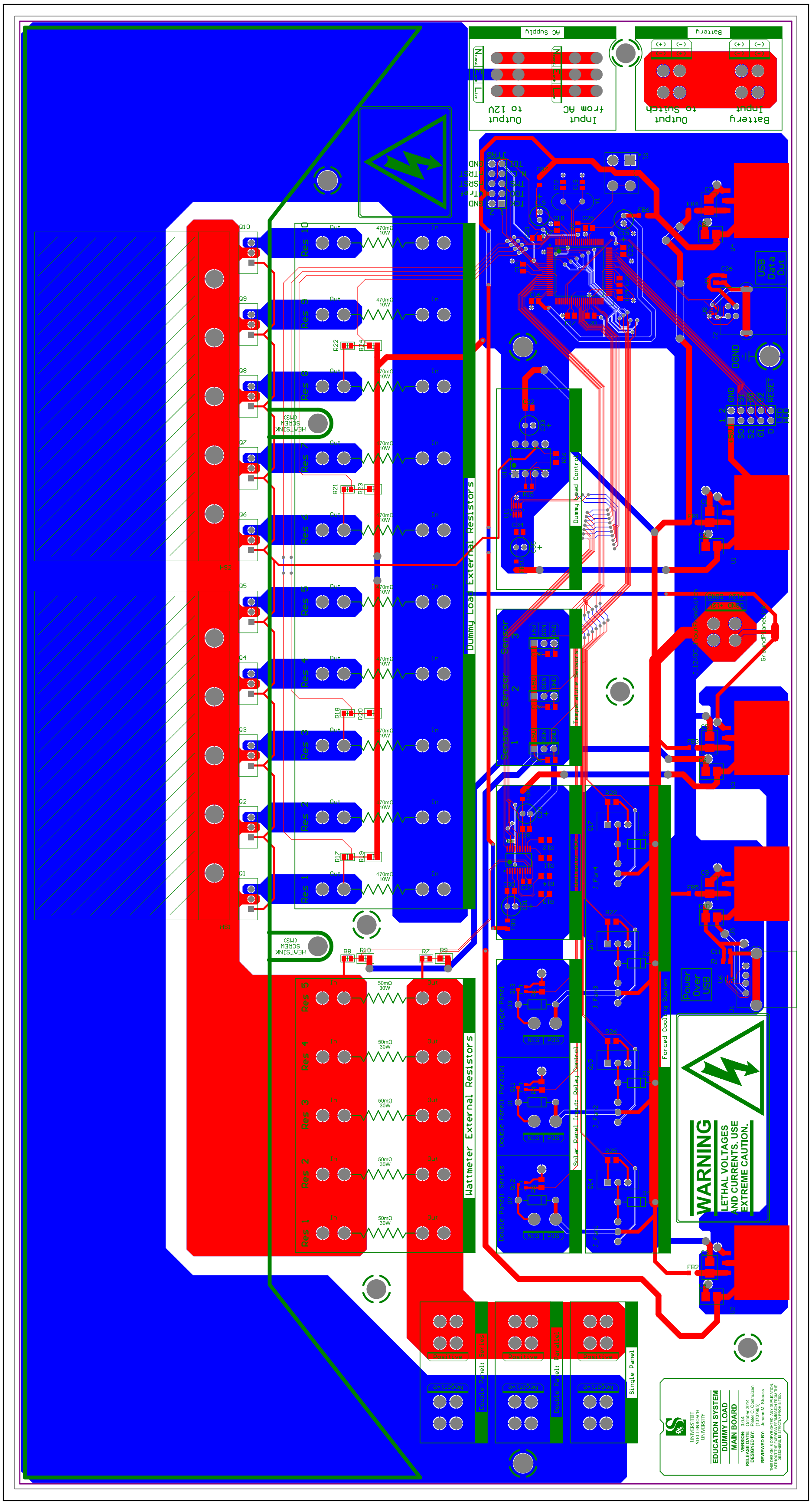
WARNING
LETHAL VOLTAGES
AND CURRENTS. USE
EXTREME CAUTION.